A Process for Determining Crown Fire Hazard and Initial Management Strategies for Ponderosa Pine Old Growth Development Areas on the Arapaho and Roosevelt National Forests

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"All models are wrong, some are useful." Anonymous

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Executive Summary

Settlement, past harvest, fire exclusion and insect activity have resulted in a low level of existing ponderosa pine old growth on the Arapaho and Roosevelt National Forests (ARNF). The 1997 ARNF Revised Forest Plan (USDA 1997b) contains Management Emphasis Goals and Objectives that relate to retaining or enhancing ponderosa pine old growth while reducing fire hazard.

The primary stand attributes that influence a fire's behavior are surface fuel loading, crown base height (CBH) and canopy bulk density (CBD). These attributes can be directly managed by vegetation treatments. Silvicultural systems can be designed to manage stands to reduce crown fire hazard but depending on how they are applied may not result in desired stand structure or species composition.

Fuel loadings, ladder fuels and proximity to private land put ponderosa pine old growth areas at risk. A process to simulate crown fire hazard change over time is not currently available. There is uncertainty if it is possible to reduce the crown fire hazard while retaining or enhancing old growth characteristic as required by Forest Plan direction.

The purpose of this analysis was to develop a process for evaluating crown fire hazard through time and recommend initial management strategies for Ponderosa Pine Old Growth on the ARNF.

The conditions that initiate and allow crown fires to spread are examined along with the process for determining site-specific values. Two indices that utilize critical open wind speeds for stand specific indicators of crown fire hazard are introduced along with the derivation of equivalent indices for the Canadian Forest Fire Behavior Prediction System (CFFBPS). Another index of crown fire hazard, the Stand Resiliency Index (SRI), was evaluated. SRI uses quadratic mean diameter (qmd) and trees per acre (tpa) as proxy for CBD.

The Forest Vegetation Simulator (FVS) (Stage 1973, Wycoff and others 1982) was used to simulate stand vegetation dynamics and the effects of alternative treatment regimes. Results of the stand projection are imported into Crown Fire Assessment for Fire Managers (CFAFM) to calculate the canopy fuel profile characteristics. CFFBPS, NEXUS and CFAFM are then used to simulate fire behavior to assess the relative fire potential in the stands through time using 90th percentile weather. The simulation results are compared to key indicators of success to determine if objectives have been met.

The simulations showed that it is possible to reduce the susceptibility of old growth ponderosa pine development areas to the initiation and spread of crown fires while maintaining or enhancing key old growth characteristics. An 8 step process was identified for the evaluation of crown fire hazard through time along with a very general treatment framework. This process can also be utilized when FFE-FVS is calibrated for the Central Rockies variant of FVS.

SRI was determined not to be a proxy for CBD as calculated in this analysis, nor any of the other crown fire indicators.

CFAFM was more applicable to this type analysis than the other fire behavior prediction tools (NEXUS and the CFFBPS) evaluated.

Overview

The Arapaho and Roosevelt National Forests (ARNF) are located along the Front Range of the Colorado Rocky Mountains. They encompass a land area of over 2.2 million acres of which 0.75 million acres are in other ownerships.

The arrangement and distribution of vegetation vary considerably across the ARNF, particularly with elevation. Ponderosa pine and Douglas-fir forest, scrublands and grasslands predominate at the lower elevations of the ARNF east of the Continental Divide. This lower montane forest region occupies an elevation range from 6000 to 8000 feet, with a growing season of about 100 days and precipitation averages of 20-25 inches per year. This lower montane forest is classed as a Type 1 fire regime where fires are the result of the interaction of wind and slope (alignment fires) or are wind driven across the landscape with little regard for topography. This fire regime was moderate to high frequency with mixed and variable (stand-replacement and nonlethal understory) magnitudes[1]. This fire regime is considered fire-dependent because fires significantly influence the functioning of the system (USDA 1997a).

Mean fire return intervals for ponderosa pine along the Front Range are cited by Laven (1980) as 45.8 years (range 3-161 years) and by Goldblum and Veblen (1992) for the pre-1859 period as 31.8 years (range 3-49 years).

Settlement, past harvest, fire exclusion and insect activity (primarily *Dendroctonus ponderosae*) have resulted in a low level of existing ponderosa pine old growth[2] on the ARNF. There are currently only 1300 acres of existing old growth and 300 acres of developing[3][4] ponderosa pine old growth within a cover type of 137,000 acres. Ponderosa pine old growth can be considered as a "habitat at risk".

The 1997 ARNF Revised Forest Plan (USDA 1997b) contains Management Emphasis Goals and Objectives that relate to retaining or enhancing ponderosa pine old growth. Specific management direction (goals, objectives and standards and guidelines) can be summarized as follows:

> *Within Ponderosa Pine old growth, stands reduce fire hazards using prescribed fire or mechanical methods. Manage acres of old growth and acres of mature forests to retain or encourage development of old growth characteristics.*

As an emphasis of the Forest Plan, old growth development areas[5] were identified during the Forest Plan management area allocations. These areas did not receive a separate management area prescription. They were identified as tentatively suitable - unavailable - old growth retention areas on the Timber Suitability Map (USDA, 1997a). Many of these old growth development

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[1] A fire regime can be described by the frequency and intensity of the fire events. Frequency is determined by ignition sources and burning conditions. Intensity is an indicator of resistance of control, while severity is a measure of impact. Collectively, intensity and severity are called a fire's magnitude (USDA, 1997a)

[2] Old-growth forests are ecosystems distinguished by old trees and related structural features. Old growth encompasses the later stages of stand development that typically differ from earlier stages in structure, composition, function and other attributes. (USDA 1992)

[3] Within the mature forest structural stage is a portion inventoried as relatively close to becoming old-growth, and termed "developing" old growth. The remainder of the mature forest stage is not considered close to becoming old growth. (USDA, 1997a).

[4] The inventory of "developing" ponderosa pine old growth is incomplete. A portion of the almost 114,000 acres of mature ponderosa pine may be capable of reaching old-growth conditions within 100 years.

[5] Old growth development areas are areas where a small core of existing or developing old growth is present and adajcent stands are added to the core to define the development area.

areas are adjacent to/or surrounded by private lands. Development pressures continue to increase on private lands. This results in continued loss of this habitat component and higher fire risk from human ignitions.

Some ponderosa pine systems have become overstocked with younger vegetation, providing a ladder for fire spread into closed canopies. Once in the canopy, because of the structure, fire can spread throughout the area. The primary stand attributes that influence a fires behavior are surface fuel loading, crown base height and canopy bulk density. These attributes can be directly managed by vegetation treatments. Silvicultural systems can be designed to manage stands to reduce crown fire hazard but if desired stand attributes are not stated the desired stand structure or species composition may not be achieved (Graham and others 1999). Mehl (1992) defines the stand attributes for ponderosa pine old growth in the USDA Forest Service Rocky Mountain Region (Region 2). Specific stand attributes include tree size, crown closure[6], trees per acre (tpa), and quantities of standing and down dead.

The Forest Vegetation Simulator (FVS) (Stage 1973, Wycoff and others 1982) is widely used to predict the effects of vegetation treatments on future stand conditions. FVS is an individual tree, distance independent growth and yield model that uses common inventory data. The model is able to simulate and is responsive to common management actions such as thinnings and regeneration harvests. It also simulates secondary growth effects including reduced mortality or increased growth. Geographic variants of FVS have been developed for most of the forested land in the western, upper mid-west, northeast and some areas of the southeast. The Central Rockies (CR) variant covers all of the National Forests in South Dakota, Wyoming, Colorado, New Mexico and Arizona (Dixon 1999). Stand conditions can be graphically depicted with the Stand Visualization System (SVS) (McGaughey 1999).

The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Beukema and others 1999) incorporates elements from existing fire behavior and fire effects models into FVS. FFE-FVS provides the ability to simulate the effects of stand development and management actions on fuel dynamics, fire behavior and effects. It also can be used to represent the effects of fire on stand development and characteristics. At this time, FFE-FVS is only calibrated for use with the Northern Idaho (NI), Eastern Montana (EM) and Southern Oregon – Northeast California (SO) variants. However, some of the methods utilized in FFE-FVS to describe the onset of crowning and to characterize crown fuels are available for use without the model.

An index called the *Stand Resiliency Index (SRI)* (Landrum and Hermit 1996) that uses quadratic mean diameter and trees per acre as a proxy to determine canopy bulk density has been proposed as a relatively easy way to rank fire hazard based upon vegetative structure. The usefulness of *SRI* in crown fire modeling or hazard rating has not been tested other than by anecdotal observations of a limited number of sites where fire behavior was modified by the structure of the vegetation.

Some local fire managers suggest that the Canadian Forest Fire Behavior Prediction System (CFFBPS) may be more applicable to analysis of crown fire hazard than the tools available in the Fire Behavior Prediction System (FBPS (US)). NEXUS and Crown Fire Assessment for Fire Managers (CFAFM) are fire behavior prediction tools that link Rothermel's (1972 1991) surface and crown fire behavior prediction models.

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[6] Stand percent canopy cover is the percentage of ground area that is directly covered with tree crowns corrected for crown overlap (Crookston 1999).

Problem Statement

Fuel loadings, ladder fuels and proximity to private land put ponderosa pine old growth development areas at risk. How does crown fire hazard change over time and is it possible to reduce the crown fire hazard while retaining or enhancing old growth characteristic as required by Forest Plan direction?

Goal Statement

Develop a process for evaluating crown fire hazard through time and recommend initial management strategies for Ponderosa Pine Old Growth to meet ARNF Forest Plan direction.

Objectives

The primary objectives of this analysis are to:

1. Determine the susceptibility of representative Ponderosa Pine old growth development stands to initiation and spread of crown fires.

2. Provide a framework to formulate treatment strategies for these representative stands that will reduce crown fire hazard while maintaining or enhancing key old growth characteristics.

The secondary objectives of this study are to:

1. Evaluate the Stand Resiliency Index (Landrum and Hermit, 1996) as a surrogate for crown fire hazard ranking based on vegetative structure.

2. Evaluate the Canadian Fire Behavior Prediction System (CFBPS), NEXUS (Scott 1999) and Crown Fire Assessment for Fuels Managers (CFAFM) (Carlton and others 2000) and their utility to the problem at hand.

Key Indicators of Success/Evaluation Criteria

Agee (1996) defines the characteristics of a "fire safe" forest to include:

- Surface fuel conditions that limit surface fireline intensity:

- Forest stands that are comprised of fire-tolerant trees, described in terms of species, sizes and structures;

- A low probability that crown fires will either initiate or spread through the forest.

Since crown fire potential is primarily dependent on the structure of the crown fuels, the regulation of crown fire potential can be approached from two complementary perspectives (Agee, 1996):

- Prevention of conditions that initiate crown fire.

    Van Wagner's (1977) crown fire model indicates that the following three quantities determine whether a crown fire will initiate:

    - *Surface fire Intensity ($I'_{initiation}$)*

- *Foliar Moisture Content (FMC)*

- *Live Crown Base Height (CBH)*

- Prevention of conditions that allow the spread of crown fire.

   Van Wagner's (1977) crown fire model also indicates that the following quantities determine whether a crown fire will be sustained:

   - *Canopy[7] Bulk Density (CBD)*

   - *Critical Surface Rate of Spread (R'_{active})*

The regulation of crown fire potential can either be at the stand or landscape level. In the following analysis, the conditions will be described at the stand level. The analysis focuses on fire hazard and fire severity and their change over time. It does not address the longer-term possible impacts of insects, disease and other disturbances on live, standing dead, surface fuel loadings and understory dynamics.

Mehl (1992) defines the stand attributes for ponderosa pine old growth in Region 2. Specific stand attributes include tree size, trees per acre, and quantities of standing and down dead. Old growth definitions for the ARNF were developed prior to the definitions for Region 2, but they are consistent with the Regional definitions (Lowry 1992). Not all attributes are considered key old growth characteristics, some may be indicators of quality. The key old growth characteristics considered in this analysis are number of large live trees and percent (%) canopy closure.

The following key indicators were identified for designing treatment strategies that relate to the primary objectives of this analysis. Along with these key indicators, the attributes and criteria for use in evaluating the treatment strategies are listed.

Table 1 – Key Indicators

Key Indicators	Attributes	Criteria
Old Growth Characteristics	Effectiveness in moving the stands towards desired old growth characteristics.	Presence of large (>18" diameter breast height (DBH)) including 15 or more trees acre^{-1} $\geq$ 12" DBH
		Crown Closure > 20%
"Fire Safe" Characteristics	Resiliency	Species Composition primarily Ponderosa pine
	Crown Fire Initiation	Crown fire does not initiate at representative weather and fuel moisture conditions. $I'_{initiation} > I$ (CBH > critical CBH)
	Active Crown Fire	Active crown fire is not sustained at representative weather and fuel moisture conditions. $R'_{active} > R_{active}$ (CBD < critical CBD)

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[7] Scott and Reinhardt (In Prep.) utilize the term canopy bulk density rather than Van Wagner's term of crown bulk density since it refers to the bulk property of the stand, not an individual tree. This convention is maintained in this analysis.

Figure 1 – Location Map

Title:

Creator:
ArcView Version 3.0
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

Where $I'_{initiation}$ is the critical I for initiating a crown fire, I is Byram's (1959) fireline intensity, R_{active} is the forward rate of spread for fully active crown fire and R'_{active} is the critical forward rate of spread for sustaining an active crown fire (Table 21). The development of the crown fire criteria is discussed in later sections.

Site Selection

Three sites[8] within Location 104521 (Table 2) were selected for analysis. Location 104521 is located within the Sheep Creek Geographic Area on the Canyon Lakes Ranger District approximately 45 air miles northwest of Fort Collins, Colorado (Figure 1).

Table 2 – List of Representative Ponderosa Pine Sites in this analysis

Site	Elevation	Aspect	Representative Condition
Station 050505	8240	Flat	N/A – Redfeather Weather Station
104521.004	8400	Southeast	Dry Site ponderosa pine – Open grown no past vegetation treatments evident
104521.016	8300	South	Ponderosa pine with history of previous vegetation treatments. Ponderosa pine understory established as result of previous treatments.
104521.018	8200	Southeast	Ponderosa pine with significant component of lodgepole pine intermediates and co-dominates

The sites were selected, as they are believed to be representative of the three most common ponderosa pine stand conditions encountered in ponderosa pine old growth development areas on the ARNF. The sites were not selected because of their physical characteristics (slope, aspect or elevation) but for their vegetative characteristics. Figures 2-4 provide a visual comparison of the sites, both photographically and graphically with Stand Visualization System (SVS) (McGaughey 1999) output [1 acre representative plots]. The sites were sampled using common stand examination techniques[9] (Table 3).

Table 3 – Inventory Conditions (1999) for Representative Ponderosa Pine Sites

	104521.004	104521.016	104521.018
Basal Area (BA) - $ft^2 acre^{-1}$	84	69	75
Tree per acre (tpa) - stems $acre^{-1}$	196	1240	162
Stand Density Index (SDI)	161	182	142
Height – feet	37	48	47
Quadratic Mean Diameter (QMD) – inches	8.9	3.0	9.3
Stand Resiliency Index (SRI)	4.1	7.0	3.9

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[8] In Region2 Location/Site in RIS (Resource Inventory System) are analogous to Compartment/Stand in used in the rest of the U.S..
[9] Stage II inventory forms are on file at the Canyon Lakes RD office in Fort Collins, CO.

Figure 2 – Site 104521.004: Dry Site Ponderosa Pine - Current Condition

Stand=521.004 Year=1999 Inventory conditions

521004_bnm_rg3_001.svs
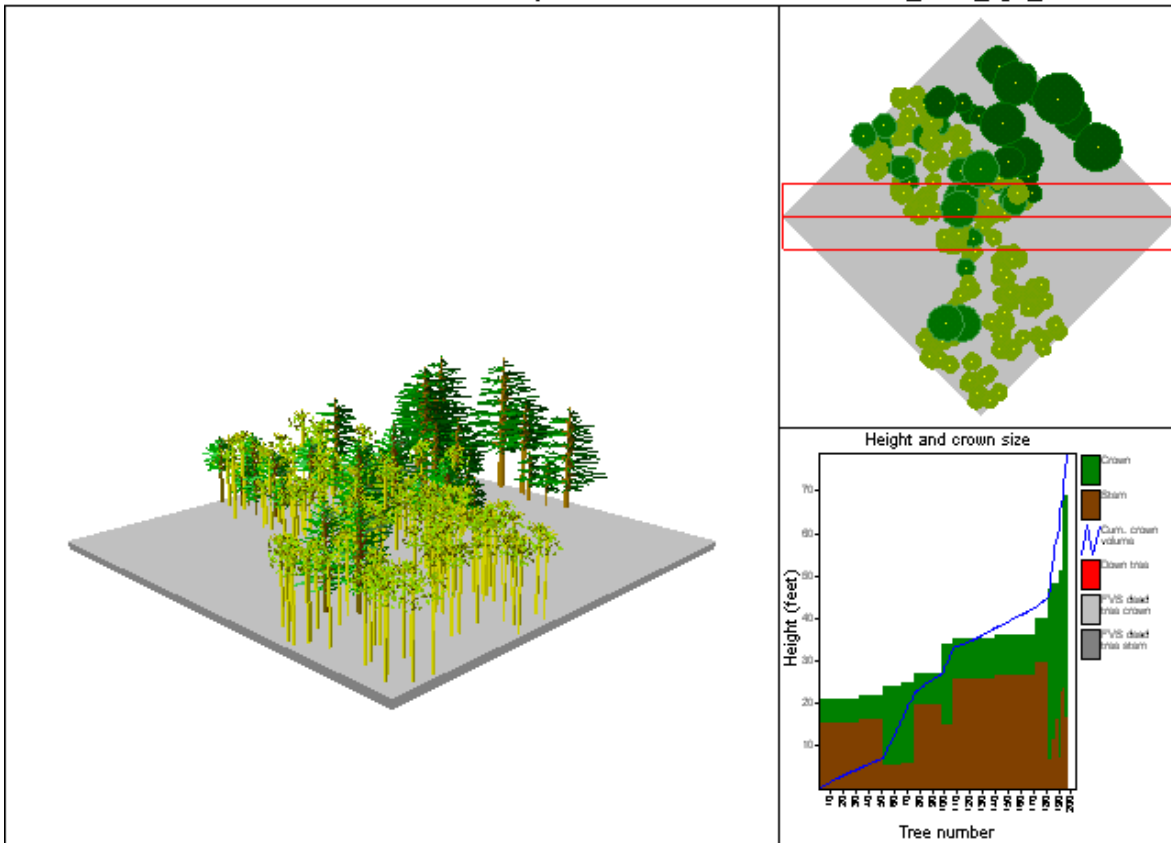
Figure 3 – Site 104521.016: Managed Ponderosa Pine - Current Condition

Stand=521.016 Year=1999 Inventory conditions   521016_bnm_001.svs
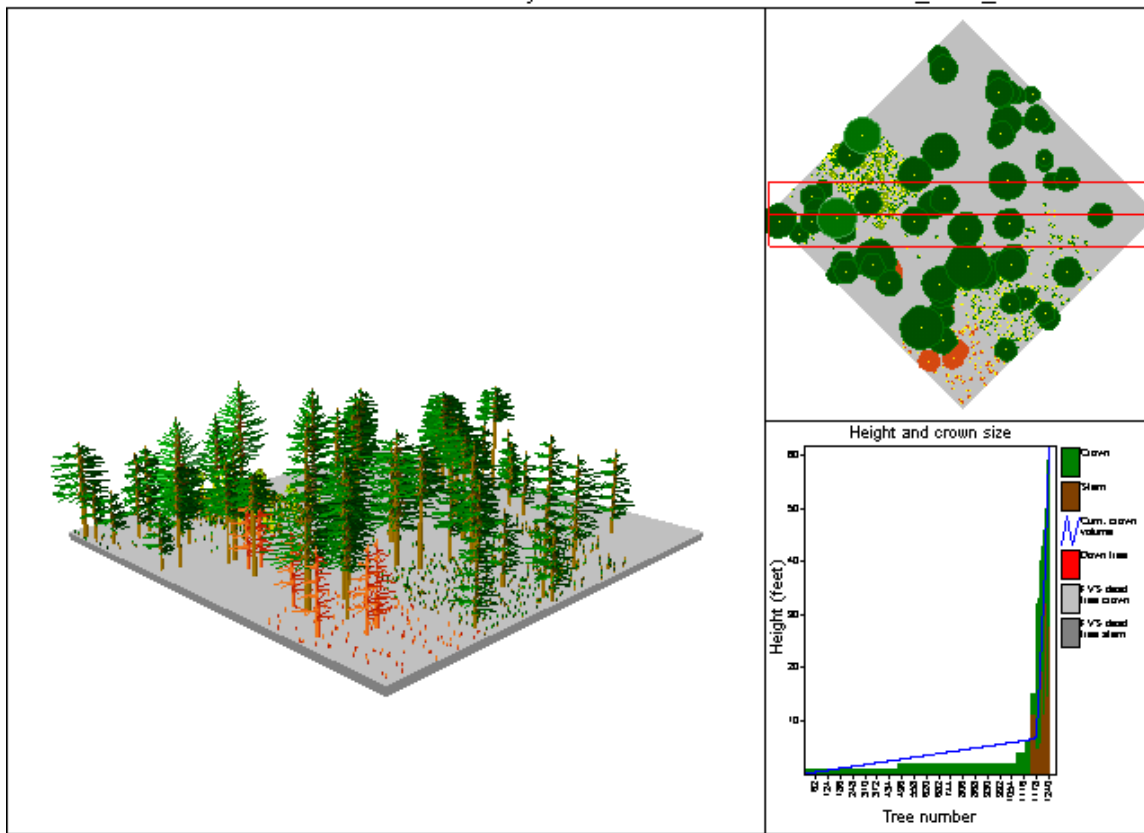
Figure 4 – Site 104521.018: Lodgepole Pine Component - Current Condition

Stand=521.018 Year=1999 Inventory conditions · 521018_bnm_001.svs
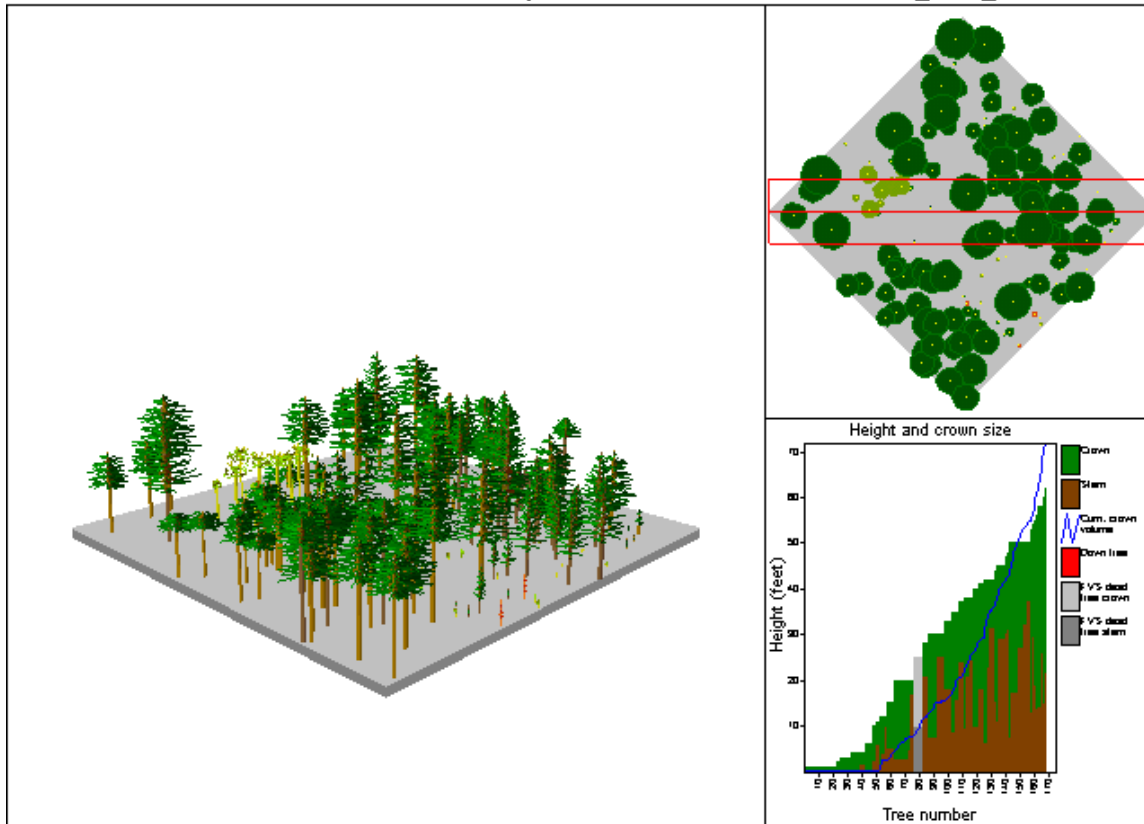
Representative Fire Weather and Fuel Moistures

Given all the possible combinations for variables of fuels, weather and topography that occur on the ARNF, it would be impossible to model all combinations. When making fire hazard assessments two methods can be employed. In the first, representative weather is utilized for making fire behavior simulations. The second method entails identifying the critical combinations of fuel moisture and windspeed that result in surface or crown fire and searching the fire weather record to determine how often these conditions exist. This requires a more detailed weather record than currently exists. Therefore, the former will be utilized.

The Redfeather Remote Automated Weather Station (RAWS) (Station 050505) is located approximately 12 miles south of the selected stands and is most representative of the selected sites. The station sits at 8240 feet and utilizes NFDRS Fuel Models G (Short Needle - heavy dead) and C (Pine Grass Savanna). Weather records[10] from the Redfeather RAWS were obtained from the forest dispatcher. The *.fwx file containing weather observations covering the period of 1964 to 1999 was imported in Fire Family Plus (FFP) for analysis. Fire records covering the period of 1971-1996 were also imported into FFP from PCHA99. The weather records were utilized to calculate 90th percentile NFDRS and CFFBPS FWI System indices.

National Fire Danger Rating System (NFDRS) Indices

Large stand replacing fire events on the ARNF are primarily wind driven events (USDA 1997a). Therefore, the wind driven fire is of primary concern. The wind directions associated with large fire events need to be determined for the percentile weather analysis in FFP. The "fire analysis" option in FFP was utilized in an attempt to determine large fire frequency as a function of wind direction. This proved to be inconclusive as the frequency of large fires was dwarfed by frequency of fire days and no discernable pattern could be identified.

Figure 5 – Large fire frequency by wind direction

Large Fire (>10 ac) Frequency By Station 050505
Wind Direction On Discovery Date -- 1971 - 1996

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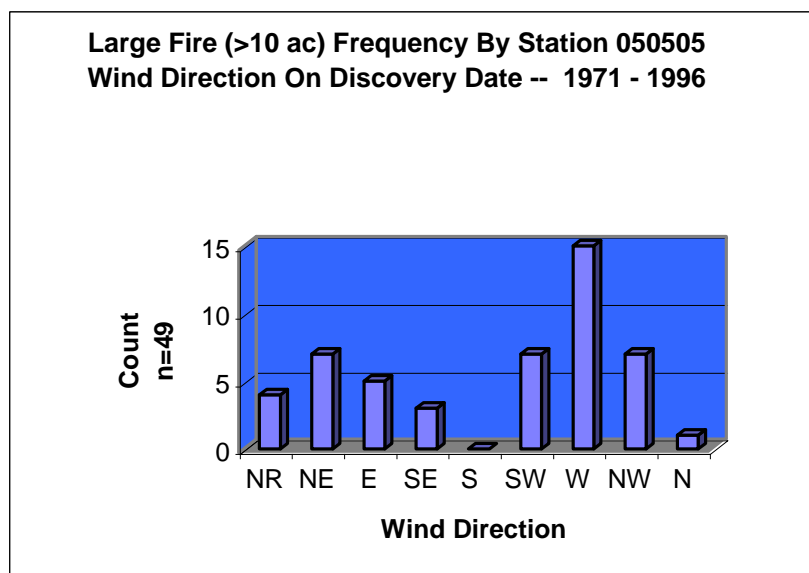
[10] These data are on file as part of the National Interagency Fire Management Integrated Database (NIFMD) in Kansas City under station number 050505

To improve the resolution the daily weather observations and fire records tables were exported from the FFP database into Excel. After sorting the fire records based upon fire size and discovery date, the tables were joined to link the weather observations corresponding with the fire discovery date. The frequency distribution shown in Figure 5 did not appear to agree with historical fire patterns on the landscape; specifically the high frequency of fires correlated with winds from the NE quadrant.

Comparing the data as acreage burned by wind direction returned a distribution of acres burned by wind direction (Figure 6) that is supported by historical fire patterns except for the acreage associated with east winds. Upon further analysis it was determined that the large acreage burned under east winds were associated with two (2) fires (#6 - 1989 and Eggers – 1994) both of which made their major runs the day after discovery. Eggers burned under the influence of west and southwest winds and #6 under the influence of strong convective winds (upslope/up valley winds resulting in an alignment fire). Therefore, for this analysis the 90th percentile weather will be determined utilizing Southwest (SW), West (W) and Northwest (NW) wind directions as they have the largest acreage loss associated with them.

Figure 6 – Large fire acreage burned by wind direction
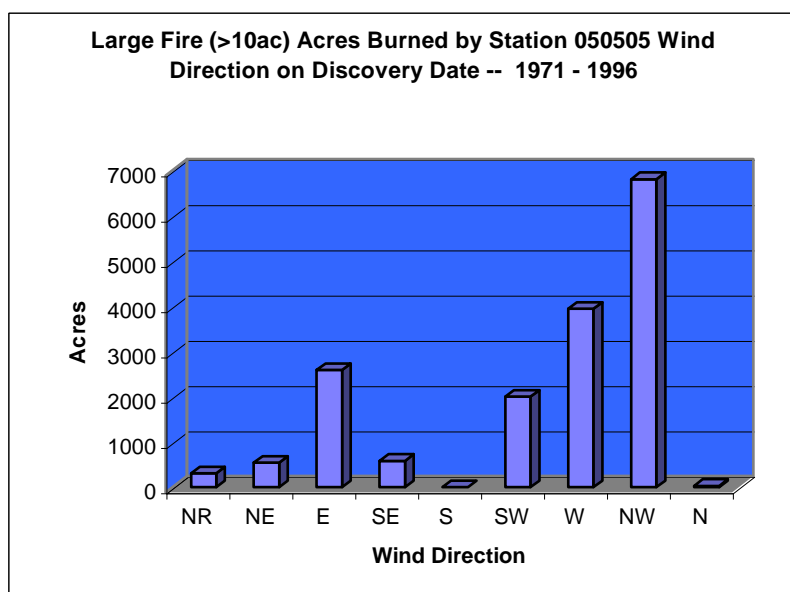
This is supported by the Windspeed vs. Direction analysis (Appendix A) for station 050505 which shows the highest proportion of winds > 12 mi hr^{-1} are related to the Southwest (SW), West (W) and Northwest (NW) wind directions. Additionally the average wind speeds for these directions are higher than winds from any of the other quadrants.

Based upon field examination there are four (4) fuel models represented to varying degrees within the stands selected for analysis, fire behavior prediction models 2, 5[11], 8 and 10 (Anderson 1982). The corresponding National Fire Danger Rating System (NFDRS) models are C, F, H and G, in that order. The station catalog information associated with each of the NFDRS models was entered into FFP. A summary of the station catalog information is contained in Appendix A.

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[11] Fuel model 5 is considered the best fit for a surface fuelbed of common juniper in terms of flame length. Rate of Spread may be underestimated. (Gleason and Lentz 2000).

Energy Release Component (ERC) was the variable selected for analysis. ERC is similar to Heat Per Unit Area (HPA) in Fire Behavior Prediction System (FBPS). The ERC traces the seasonal trend of fire danger better than the other NFDRS indices, as it is least responsive to short term fluctuations in fire danger (Deeming and others 1978). The percentile range and midpoint values utilized in the 90th percentile analysis of each NFDRS model are shown in Table 4.

Table 4 – ERC percentile ranges and midpoint values

	ERC Percentile Range	ERC Midpoint Value
Low	0-30	25th%ile
Moderate	31-85	50th%ile
High	86-95	90th%ile
Extreme	96-100	97th%ile

The 90th percentile weather for the four NFDRS fuel models[12] used in this analysis is detailed in Table 5.

Table 5 – 90th percentile weather

Station: 050505				
Variable: ERC				
Data Years: 1964 - 1999				
Date Range: April 15 – October 31				
Wind Directions: SW, W, NW				
FBPS Model	**2**	**5**	**10**	**8**
NFDRS Model	**C**	**F**	**G**	**H**
Percentile Probabilities and Mid-points				
Variable/Component Range	High	High	High	High
Percentile Range	86-95	86-95	86-95	86-95
Climatological Probability	10	10	10	10
Mid Point ERC	15 - 15	24 - 24	54 - 54	30 - 31
Calculated Spread Component	25	13	17	5
Calculated ERC	16	24	55	31
Fuel Moistures				
1 hour Fuel Moistures	4.90	3.80	4.70	4.10
10 hour Fuel Moistures	5.90	5.00	6.90	6.30
100 hour Fuel Moistures	10.80	9.20	8.60	8.20
Herbaceous Fuel Moisture	31.20	70.90	60.20	55.00
Woody Fuel Moisture	76.90	100.60	93.30	87.00
20 Foot Wind Speed mph	14.70	13.20	13.10	12.80
1000 hour Fuel Moisture	14.40	13.70	12.50	12.70

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[12] Percentile weather analysis reports for all NFDRS fuel models are contained in Appendix A.

Canadian Forest Fire Danger Rating System (CFFDRS) Indices

The CFFDRS will consist of four modules or subsystems when complete. The Canadian Forest Fire Weather Index (FWI) system, the Canadian Forest Fire Behavior Prediction System (CFFBPS), a fire occurrence prediction system and an accessory fuel moisture system (Stocks and others 1989).

The FWI System consists of six components that individually and collectively account for the effects of fuel moisture and wind on fire behavior. There are three fuel moisture codes, the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC) and the Drought Code (DC) which provide numerical ratings of the fuel moisture content of the fine surface litter layer, loosely compacted duff (moderate depth) and deep organic matter respectively. The three fire behavior indices, the Initial Spread Index (ISI), the Buildup Index (BUI) and the Fire Weather Index (FWI) are intended to represent rate of spread, fuel available for combustion and frontal fire intensity (Stocks and others 1989).

The three fuel moisture codes plus wind are linked in pairs to form two intermediate indices and one final index. ISI combines the effects of wind and fine fuel moisture content represented by the FFMC. It represents a numerical rating of the final rate of spread without the influence of variable fuel quantity. The BUI combines the DMC and DC into a numerical rating of the total fuel available for combustion. The FWI combines the ISI and BUI to represent a relative measure of the potential intensity of a single spreading fire in a standard fuel complex. The FWI is best used as a measure of general fire danger (Stocks and others 1989).

The FWI System components have different interpretations in different fuel types as the FWI System represents fire behavior in a generalized fuel type. This variation in fire behavior is addressed in the CFFBPS subsystem (Stocks and others 1989).

To put the CFFDRS indices into perspective the following is a brief discussion of the difference between NFDRS and FWI. To evaluate the worst-case fire danger NFDRS estimates the moisture content of roundwood, without bark, off the ground, and in the open. The FWI estimates the moisture content of surface litter and duff under a canopy. Because it predicts fire danger in the open, NFDRS reaches peak values quickly and remains relatively high under continued drying. In doing so, however the system may lose some ability to distinguish between varying degrees of high to extreme danger under a closed canopy. Because FWI predicts fire danger under a canopy it responds more slowly than NFDRS and may therefore be better able to distinguish fire danger peaks in forest stands (Simard and others 1983) A major difference between the systems is in the response of the two systems immediately after a rainfall of 0.1 inch or more.

The CFFBPS has 16 general fuel types including 7 conifer, 1 deciduous, 4 mixed wood, 3 slash and 1 open grass type. It is an empirical model; the fire behavior relationships within the system are based on observations of actual fire behavior, both field experiments and documented wildfires. The CFFBPS uses the FFMC, the ISI and BUI from the FWI System. These indices are considered weather inputs because they are calculated from standard weather observations. The system also requires input of the Foliar Moisture Content (FMC). FMC is related to the prediction of crown fire involvement (Hirsch 1996).

The primary outputs of CFFBPS are rate of spread, fuel consumption, head fire intensity and fire description (crown fraction burned and fire type) (Forestry Canada Fire Danger Group 1992).

The FWI was chosen as the variable of interest for percentile weather as it roughly equivalent to I in Byram's (1959) equation where ISI = R and BUI = W_f and H is a constant.

$$I = \frac{HW_fR}{60}$$

H is the heat yield of the fuel, W_f is the weight of fuel consumed in the flaming front, *R* is the forward rate of spread of the fire and 60 is a conversion factor so that the units for *I* are in kW m^{-1} or BTU ft^{-1} basis as defined in Table 8.

A wide range of FWI System inputs can be combined to produce an identical FWI. Calculating the 90th percentile FWI System values was more problematic than the NFDRS values. FWI System indices are not valid options for analysis under the percentile weather analysis in FFP. Two alternative methods to obtain the 90th percentile were explored and evaluated. The first option utilized was an independent analysis of each input variable (FFP>weather>season reports>severity summary>*index_name*). Upon examination, this method yielded values that were unrelated.

The second method utilized was to run 90th percentile for FWI[13] (weather>season reports >severity summary> FWI). After finding this value, a daily listing report of all the FWI System indices was prepared (FFP>weather>season reports >daily listing>select all Canadian indices along with wind). This text file was then imported into Excel and sorted by FWI and date. The 90th percentile FWI value was located and the indices for the corresponding days were analyzed using the descriptive statistics option in Excel. The means for the indices are then utilized as the 90th percentile values. The 90th percentile weather for the FWI System indices used in this analysis is detailed in column 1 of Table 6.

Table 6 – 90th Percentile values for FWI System indices.

Station: 050505			
Variable: FWI			
Data Years: 1964 - 1999			
Date Range: April 15 – October 31			
Wind Directions: All			
	Station 050505 Analysis	Black Tiger July 9, 1989 Actual	Station 050505 July 9, 1989 Actual
FWI (Fire Weather Index)	54.6	59	78.8
BUI (Build Up Index)	82.5	111	112.7
FFMC (Fine Fuel Moisture Code)	96.0	95.2	96.0
DMC (Duff Moisture Code)	62.4	111	112.8
DC (Drought Code)	334.6	269	267.9
ISI (Initial Spread Index)	27.7	24.5	39.9
DSR (Daily Severity Rating)	32.3	-----	61.9
20 Foot Wind Speed mph	11.0	-----	15.0
10 meter Wind Speed mph [14]	12.7	-----	17.3

To provide a point of comparison, the FWI System indices for July 9, 1989 for the Black Tiger Fire (Alexander 1990) near Boulder Colorado and the Redfeather RAWS are included in Table

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[13] The Percentile weather analysis report for FWI is contained in Appendix A.

[14] U.S. standard 20-foot open windspeed adjusted to the CFFDRS 10 meter standard by applying a factor of 1.15 as recommended by Turner and Lawson (1978).

6. The Black Tiger Fire (NFPA, 1990) burned under exceedingly severe burning conditions. The NFDRS fuel model C values for July 9, 1989 are shown in table 7 for further comparison.

Table 7 – NFDRS Values for July 9, 1989

Station: 050505	
Variable: ERC	
NFDRS Model	C
ERC	14.3
Fuel Moistures	
1 hour Fuel Moistures	3.6
10 hour Fuel Moistures	6.0
100 hour Fuel Moistures	5.5
Herbaceous Fuel Moisture	64.1

The FWI scale is consistent across Canada but the class boundaries for fire danger classifications vary. In western Canada a FWI greater than 25 would be rated as an extreme fire danger class (Stocks and others 1989) however without breaking down the danger classes (Van Wagner 1987) for the Redfeather RAWS, it is unknown whether this relationship is valid for this area.

Foliar Moisture Content

Foliar Moisture Content (FMC) is a required input to determine the potential crown fire initiation (Van Wagner 1977) in the CFFBPS, NEXUS and CFAFM. There are various methods that can be utilized for estimating this value. The CFFBPS allows for the calculation of FMC according to calendar date, geographical location and elevation (Forestry Canada Fire Danger Group 1992). This method is based upon a limited geographic range of data. If site specific data is not available for calculating foliar moisture content, an estimated value between 100 and 120% may be used (Rothermel 1983, Forestry Canada Fire Danger Group 1992).

A Live Fuel Moisture monitoring program has been ongoing on the ARNF near the Redfeather RAWS since late 1989.

Figure 7 – Foliar Moisture Content
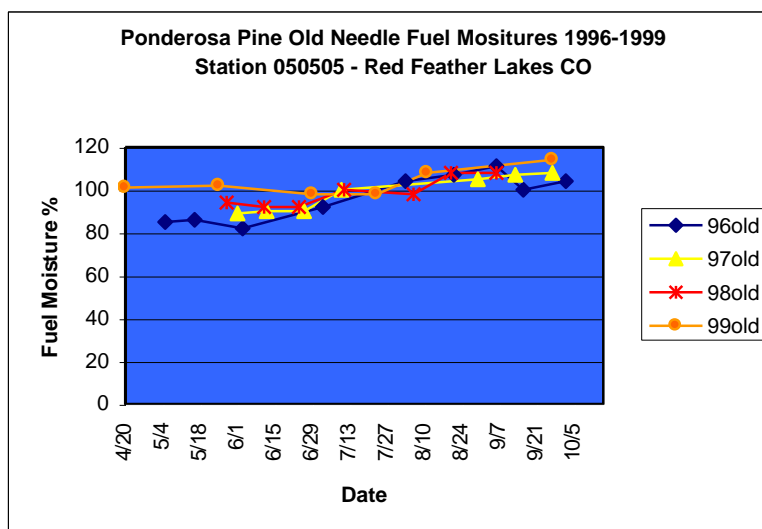
Unfortunately, the monitoring was not conducted in a consistent manner until 1996. The data from this monitoring program beginning with the 1996 data was entered into an Excel spreadsheet. Figure 7 is a graphical representation of the data on a yearly basis.

The data analysis option for percentiles in Excel was utilized to calculate the 10th, 50th and 90th percentiles. The results were 88%, 99% and 108% respectively. The actual FMC for the Black Tiger Fire was 110% (Alexander 2000). Based upon the FMC trend, the 50th percentile FMC (99%) will be utilized as this level of FMC appears to occur at the same general time of year as the 90th percentile FWI and ERC (Early summer and possibly late fall).

Conditions That Initiate and Allow Crown Fires to Spread

Initiation and sustained spread of crown fires is dependent on surface fuels and crown fuels. Rothermel (1972 and 1991) presents separate method for surface fire behavior and crown fire behavior but not a transition between them. Rothermel's (1991) crown fire model does not include the effect of canopy bulk density on fire spread and is based upon observations of seven fires that he believed to have been wind driven. Van Wagner's (1977) model of transition to crown fire provides the links between surface and crown fire models. It requires estimates of crown base height and canopy bulk density (Reinhardt and others 1999).

Canopy Fuel Characteristics

There is very little guidance for determining canopy fuel characteristics at the stand level. Crown base height (CBH) is a simple measurement on individual trees but not well defined for a stand of trees. Stand CBH has been defined by as the lowest CBH occurring in the stand (Graham and others 1999), as the mean height of the crown bases and by Sando and Wick (1972) as the mean height above ground containing a minimum of 100 pounds per acre per vertical foot[15] (0.037 kg m^{-3}).

Canopy Bulk Density (CBD) is crown biomass divided by the volume occupied by the crown fuels. It is a characteristic of the stand not an individual tree. CBD is also very difficult to assess. It can not be directly measured except through destructive sampling. (Reinhardt and others In Prep.)

Figure 8 – Hypothetical Canopy Fuel Profile (Reinhardt and others 1999)
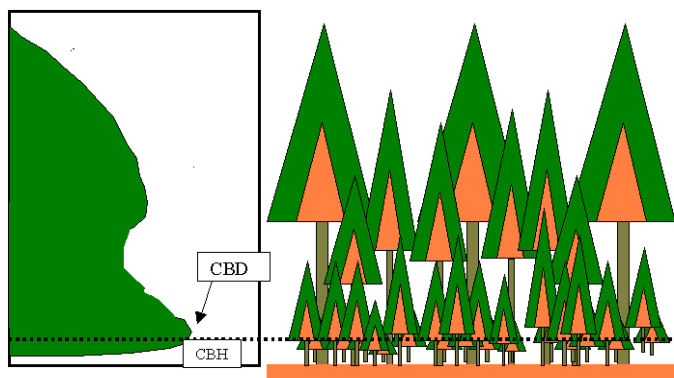
Reinhardt and others (In Prep.) provide a standardized method for estimating effective CBH and CBD based upon Sando and Wick's procedure. Crown Base Height is the lowest height at which

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[15] Although Sando and Wick's selection of 100 pounds per acre per vertical foot was largely arbitrary, Scott and Reinhardt (In Prep.) found that results for sample stands seemed to agree favorably with visual inspections.

a running mean of the canopy bulk density exceeds the minimum of 100 pounds per acre per vertical foot (0.037 kg m^{-3}) (Figure 8). Canopy Bulk Density is the maximum of the running mean. Brown's (1978) equations are used for estimating the weight of foliage and small branchwood for each tree applied to a stand list. One disadvantage of this method is the exclusion of understory trees < 1.0" DBH. Scott and Reinhardt (In Prep.) suggest that these ladder fuels, which increase the intensity of surface fire, are best accounted for through custom surface fuel modeling or by adjusting the predicted surface fire intensity. However, if a significant understory exists (tpa), critical CBD may be attained in the understory (Hood 2000).

This procedure has been incorporated into FFE-FVS (Beukema and others 1999) and CFAFM (Carlton and others 2000).

Conditions for Crown Fire Initiation

The initiation of crown fire behavior is a function of the surface fire intensity and the canopy fuel characteristics of CBH and FMC. When the surface fire intensity (I) attains or exceeds the critical surface intensity for crown combustion ($I'_{initiation}$) fire can propagate vertically through the canopy. After Van Wagner (1977) the equations to calculate the critical surface fire intensity ($I'_{initiation}$ in kW m^{-1} or BTU ft^{-1} sec^{-1}) are:

$$I'_{initiation} = \left(\frac{CBH(460 + 25.9FMC)}{100} \right)^{1.5} \qquad \text{kW m}^{-1} \quad \text{(Alexander, 1988)}$$

$$I'_{initiation} = \left(0.0030976 * CBH * (197.90 + 11.186FMC) \right)^{1.5} \quad \text{BTU ft}^{-1} \text{ sec}^{-1} \quad \text{(Alexander, 1988),}$$

where *CBH* is in meters and feet respectively and *FMC* is in percent. The critical level of fireline intensity appears to be more sensitive to CBH than to FMC (Agee 1996).

$I'_{initiation}$ can be converted to an equivalent critical surface rate of spread ($R'_{initiation}$) by rearranging Byram's (1959) equation and substituting $I'_{initiation}$ for I :

$$R'_{initiation} = \frac{60I'_{initiation}}{HPA} \qquad \text{m min}^{-1} \text{ or ft min}^{-1} \qquad \text{(Scott and Reinhardt In Prep.)}$$

where $R'_{initiation}$ is either m min^{-1} or ft min^{-1} with $I'_{initiation}$ in kW m^{-1} or Btu ft^{-1} sec^{-1} and *HPA* is heat per unit area in either kJ m^{-2} or Btu ft^{-2} respectively.

Conditions for Active Crown Fire Spread

The ability of a crown fire to spread is a function of the surface rate of spread and the CBD. Van Wagner (1977) proposed that there is a theoretical lower limit for CBD, below which crown fire will not actively spread (Alexander 1988). After Van Wagner (1977) and Alexander (1988) the equations to calculate the critical rate of spread (R'_{active} in m min^{-1} or ft min^{-1}) for sustaining active crown fire spread are:

$$R'_{active} = \frac{3.0}{CBD} \qquad \text{m min}^{-1} \text{ Alexander (1988)}$$

$$R'_{active} = \frac{0.614431535}{CBD} \qquad \text{ft min}^{-1}$$

where CBD is in kg m^{-3} or lbs ft^{-3} respectively.

Environmental Conditions for Initiation and Sustained Spread of Crown Fires

Scott and Reinhardt (In Prep.) propose two alternate indices of crown fire potential that do not rely on extensive climatology. The indices use the critical open windspeeds[16] for crown fire initiation and active spread as stand specific indicators of crown fire hazard. They are the Torching and Crowning Index. The complete derivations for determining the indices are described in Scott and Reinhardt (In Prep.) and are summarized in the following sections.

Fire Behavior Prediction System - FBPS (US)

The *Torching Index* (*TI*) is the US standard 20-foot open wind speed at which $R'_{initiation} = R_{surface}$ for a specific set of surface fuel moistures. It is the 20-foot windspeed at which a surface fire is expected to ignite the crown layer. It is a function of surface fuel characteristics (fuel model), surface fuel moistures, CBH, FMC, and wind reduction factor by the canopy. TI may be expressed in either km hr^{-1} or mi hr^{-1}.

$$TI = O'_{initiation} = \left(\frac{1}{54.683 WRF}\right)\left(\frac{\dfrac{60 I'_{initiation}\rho_b \varepsilon Q_{ig}}{HPA \xi I_R} - \phi_s - 1}{C\left(\dfrac{\beta}{\beta_{op}}\right)^{-E}}\right)^{\frac{1}{B}} \qquad \text{km hr}^{-1}$$

$$TI = O'_{initiation} = \left(\frac{1}{88 WRF}\right)\left(\frac{\dfrac{60 I'_{initiation}\rho_b \varepsilon Q_{ig}}{HPA \xi I_R} - \phi_s - 1}{C\left(\dfrac{\beta}{\beta_{op}}\right)^{-E}}\right)^{\frac{1}{B}} \qquad \text{mi hr}^{-1}$$

where the variables are defined in Table 21.

The *Crowning Index* (*CI*) is the US standard 20-foot open wind speed at which $R'_{active} = R_{active}$ for a specific set of surface fuel moistures. It is the 20-foot windspeed at which active crowning is possible based on Rothermel's (1991) crown fire spread rate model and Van Wagner's (1977) criterion for active crown fire spread. It is a function of CBD, slope steepness and surface fuel moisture content. *CI* may be expressed in either km hr^{-1} or mi hr^{-1}.

$$CI = O'_{active} = 0.0457\left(\frac{\dfrac{164.8 \varepsilon Q_{ig}}{I_R CBD} - \phi_s - 1}{.001612}\right)^{0.7} \qquad \text{km hr}^{-1}$$

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[16] Although the critical open windspeeds are used as the indices, it is the site conditions (surface and canopy fuels, slope etc) not the weather that is being rated (Scott and Reinhardt In Prep.).

$$CI = O'_{active} = 0.02841 \left(\frac{\dfrac{1.98745\varepsilon Q_{ig}}{I_R CBD} - \phi_s - 1}{.001610} \right)^{0.699} \qquad \text{mi hr}^{-1}$$

where the variables are defined in Table 21.

Although it is possible to calculate the *TI* and *CI* including the effect of cross slope winds the above indices are for upslope winds only. *TI* and *CI* were originally incorporated into NEXUS and FFE-FVS only. CFAFM was modified to include *TI* and *CI* specifically for this analysis.

Canadian Forest Fire Behavior Prediction System

By solving initial rate of spread *(RSI)* for *ISI* (and incorporating the foliar moisture effect in the crown fire equation) indices analogous to the Torching and Crowning Indices developed for the U. S. system can be derived (Reinhardt and Scott In Prep.).

The general form of the rate of spread equation (fuel models C-1 to C-5 and C-7) is: $RSI = a \times \left[1 - e^{(-b \times ISI)} \right]^c$ (m min⁻¹) where a, b, and c are Canadian Fuel Model Parameters and *ISI* is the FWI weather input (Forestry Canada Fire Danger Group 1992).

By solving for *ISI = ISI'initiation* the TI is expressed (in terms of *ISI*) as:

$$TI = ISI'_{initiation} = \frac{Ln\left[1 - \left(\dfrac{RSO_{initiation}}{a} \right)^{\frac{1}{c}} \right]}{-b}$$

where *RSO'initiation* = Critical Rate of Spread for initiating a crown fire in m min⁻¹ and a, b, and c are Canadian Fuel Model Parameters. *RSO'initiation* (eq. 57) is a function of CBH, FMC and surface fuel consumption (SFC). *SFC* is an exponential function (eqs. 9-25) of the *BUI* and for some models, the *FFMC* (Forestry Canada Fire Danger Group 1992).

By solving for *ISI = ISI'active* the CI is expressed (in terms of *ISI*) as:

$$CI = ISI'_{active} = \frac{Ln\left[1 - \left(\dfrac{RSO_{active}}{a * \left(\dfrac{ME}{FME} \right)} \right)^{\frac{1}{c}} \right]}{-b}$$

RSO'active = *R'active* the critical rate of Spread for sustaining an active crown fire. *RSO'active* is a function of CBD. ME/FME = Foliar Moisture Effect and a, b, and c are Canadian Fuel Model Parameters (Forestry Canada Fire Danger Group 1992).

These indices show the combined effect of fuel moisture and wind since *ISI* is function of those weather observations.

It is possible to derive analytical solutions for TI and CI in terms of net-vectored wind speed (combined effect of slope and wind speed) (*WSV*). Starting with the base ISI equation: (where the variables are defined in Table 21):

$$ISI = 0.208 \times f(W) \times f(F)$$ eq. 52 (Forestry Canada Fire Danger Group 1992).

where $f(W) = e^{0.0503 \times WSV}$ eq. 53 (Forestry Canada Fire Danger Group 1992).

Solving for *WSV* where $ISI = ISI'_{initiation}$

$f(W) = \dfrac{ISI'_{initiation}}{0.208 \times f(F)}$ Substituting $e^{0.0503 \times WSV}$ for $f(W)$, *TI* is calculated as follows:

$$TI_{wsv} = \frac{\left(Ln \left(\dfrac{ISI'_{initiation}}{0.208 \times f(F)} \right) \right)}{0.05039}$$ km hr^{-1} at 10 meter where

$$f(F) = 91.9 \times e^{(-0.1386 \times m)} \times \left[1 + \frac{m^{5.31}}{4.93 \times 10^7} \right]$$ eq. 45 (Forestry Canada Fire Danger Group 1992).

and $m = \dfrac{147.2 \times (101 - FFMC)}{59.5 + FFMC}$ eq. 46 (Forestry Canada Fire Danger Group 1992).

CI_{wsv} is calculated similarly by solving for $ISI = ISI'_{active}$

$$CI_{wsv} = \frac{\left(Ln \left(\dfrac{ISI'_{active}}{0.208 \times f(F)} \right) \right)}{0.05039}$$ km hr^{-1} at 10 meter where

$$f(F) = 91.9 \times e^{(-0.1386 \times m)} \times \left[1 + \frac{m^{5.31}}{4.93 \times 10^7} \right]$$ eq. 45 (Forestry Canada Fire Danger Group 1992).

and $m = \dfrac{147.2 \times (101 - FFMC)}{59.5 + FFMC}$ eq. 46 (Forestry Canada Fire Danger Group 1992).

Both CI_{wsv} and TI_{wsv}[17] can be converted to mi hr^{-1} by multiplying km hr^{-1} x 0.621. This is the CFFDRS 10 meter standard .

The CI_{wsv} and TI_{wsv} at the CFFDRS 10 meter standard in mi hr^{-1} can be adjusted to the U.S. standard 20 foot open windspeed by dividing by a factor of 1.15 as recommended by Turner and

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[17] ISI'_{active} and CI_{wsv} will not be calculated in instances of low CBD (<0.066 kg m^{-3}). In addition, $ISI'_{initiation}$ and TI_{wsv} do not calculate when CBH is high or $RSO_{initiation}$ is above 44 m min^{-1} (i.e.: 200-feet). The correct interpretation is that the conditions are such that either torching or crown fire will not develop under those stand conditions. (Reinhardt, personal com, 2000). These observations are limited to the results of this analysis only. They are based upon fuel model C-7 only and may be valid only for this set of FWI system inputs only.

Lawson (1978). This provides a more direct comparison with *TI* and *CI* calculated in the FBPS (US).

CI_{wsv}, TI_{wsv}, $ISI'_{initiation}$ and ISI'_{active} are not standard outputs of CFFBPS. They were incorporated into an Excel spreadsheet, using outputs from CFFBS and CFAFM (CBD), specifically for this analysis.

Other Indices of Crown Fire Hazard

Landrum and Hermit (1996) propose that the quadratic mean diameter and trees per acre for a site can be used as a proxy to determine canopy bulk density (CBD). The vertical fuel profile (continuity, tree size and tree density) can be considered in an index called the *Stand Resiliency Index (SRI)*. It is calculated from inventory data using the formula:

$$SRI = 1 + \ln\left[\frac{tpa}{qmd}\right]$$ where qmd = quadratic mean diameter and tpa = trees per acre.

The relative rankings of fire hazard with SRI are: <3 (low), 3-4 (Medium) and > 4 (High). SRI would offer a relatively easy way to rank fire hazard based upon vegetative structure if it correlates with CBD or another crown fire hazard parameter such as CBH. The usefulness of *SRI* in crown fire modeling or hazard rating has not been tested other than by anecdotal observations of a limited number of sites where fire behavior was modified by the structure of the vegetation.

Types of Crown Fire

Van Wagner (1977) identified three types of crown fire:

- Passive – also called torching, is one where individual trees or small groups are ignited but rate of spread is controlled by the surface rate of spread.

- Active – also called continuous (Forestry Canada Fire Danger Group 1992), is one that advances with a well-defined wall of solid flame extending from the surface to above the tree canopy (Alexander 1988).

- Independent – is one that advances in the canopy fuel well ahead of (or in the absence of) the surface fire, requiring none of the surface fire's energy for sustained spread. They are not usually addressed because they rarely occur and no model of their behavior is available (Reinhardt and Scott In Prep.).

Forestry Canada Fire Danger Group (1992) provides another definition of passive crown fire. They term it intermittent. This describes a fire that lies between surface and active (continuous). This includes fires with just isolated torching as well as fires that are actively torching but have not yet reached the active stage.

Although there is relative agreement on the definition of crown fire, the fire behavior prediction tools utilized in this analysis employ slightly different criteria for defining fire type.

- CFFBPS – Fire type (Table 8) is determined by Crown Fraction Burned (CFB).

- CFB will always be 90% if ROS exceeds RSO (Critical Spread Rate for Crowning) by 10 m/min.

Table 8 – Types of fires used in the CFFBPS (Hirsch 1996)

Type of Fire	Crown Fraction Burned
Surface Fire	<0.1
Passive (Intermittent) crown fire	0.1 – 0.89
Active (Continuous) crown fire	≥ 0.9

- CFAFM – Fire type is determined using Van Wagner's (1977) threshold criteria.

   Table 9 - Classification of fire types using Van Wagner's (1977) threshold criteria. $I_{surface}$ is predicted from basic intensity equations in FBPS (US) and R_{active} from Rothermel (1991). $I'_{initiation}$ and R'_{active} are from Van Wagner (1977). (Scott and Reinhardt In Prep.)

	$R_{active} < R'_{active}$	$R_{active} > R'_{active}$
$I_{surface} < I'_{initiation}$	Surface fire	Surface fire
$I_{surface} > I'_{initiation}$	Passive crown fire	Active crown fire

- NEXUS - Fire type is determined by Crown Fraction Burned (CFB) as in Table 8. There are three equations available for the calculation of CFB: exponential, modified exponential (Farsite) and straight line. Scott and Reinhardt (In Prep.) recommend using the straight-line equation. (CFAFM and CFFBPS utilize the exponential form for calculating CFB). CFB affects the final surface fireline intensity in both NEXUS and CFFBPS.

- FFE-FVS - Fire type is determined similar to CFAFM except using Torching and Crowning Indices.

   Table 10 - Classification of fire types using Torching and Crowning Indices in FFE-FVS (Beukema and others 1999)

	TI < Wind Speed	TI > Wind Speed
CI > Wind Speed	Passive crown fire	Surface fire
CI < Wind Speed	Active crown Fire	

Analysis Methods and Assumptions

The Forest Vegetation Simulator (FVS) (Stage 1973, Wycoff and others 1982) was used to simulate stand vegetation dynamics and the effects of treatment regimes. The results of the stand projection are imported into CFAFM to calculate the canopy fuel profile and characteristics. CFFBPS, NEXUS and CFAFM are then used to simulate fire behavior to assess the relative fire potential in the stands through time. The simulations are not designed to predict the behavior of an actual fire. The simulation results are then compared to the key indicator criteria to determine if objectives have been met. The Stand Visualization System (SVS) (McGaughey 1999) was used to graphically view the stand condition at critical times in the simulation.

FVS

The Central Rockies (CR) variant of FVS was the utilized to simulate the stand/site vegetation dynamics and the effects of treatment regimes on crown fire hazard. The simulations did not model snag, woody debris, or fuel model dynamics.

The Suppose graphical user interface (Crookston 1997) for FVS was utilized to build the simulation keyword file. The keyword file contains the key elements of proposed management regimes required for running FVS simulations. Statements for computing stand structure variables, generating tree lists for use in SVS and canopy fuel characteristic calculations are also included. Common keyword elements for all sites were passed to an "add file" which could be utilized for each simulation. The keyword add file is contained in Appendix B.

FVS uses a concept called "tripling", where each tree record for the first several cycles is split into three records. Tripling is a mechanism to increase the number of records to help stabilize the random effects of the projections (FMSC 1999b). In sites with significant stocking, this can result in tree lists with up to 1350 records/cycle. Such a large number of tree records were cumbersome to handle for canopy fuel characteristics calculations. The "NoTriple" keyword was utilized for all projections.

Somewhat more problematic is the fact that the CR variant does not simulate natural regeneration without use of keywords for the Regeneration Establishment Model (Ferguson and Crookston 1991). Since small trees represent a source of ladder fuels, regeneration must be simulated during the projection periods. The general assumption utilized was that only minor amounts of regeneration (50 tpa per 20 year cycle) would occur during cycles with no active intervention. Regeneration following some interventions was simulated at higher amounts (100 tpa) if the intervention was believed to be of sufficient intensity to warrant other than incidental regeneration during that cycle. The regeneration keywords utilized are contained in Appendix B.

All simulations were run on 10-year cycles for a 100-year projection period. A projection period of 100 years was utilized to be consistent with the definition of "will be old growth". The "will be old growth" designation is applied to stands that are expected to meet old growth characteristics within 100 years.

The TOSS post processor was utilized to select only the Stand Summary Statistics and Structural Statistics Tables (Crookston 1999) for printing. These reports are contained in Appendix B.

Crown closure is estimated from the stand structural statistics (Crookston 1999).

Each site was simulated under a No Management alternative and at least one alternative with a silvicultural intervention during the projection period (Appendix B).

[For a detailed description of FVS and Suppose see FMSC 1999, Teck and others 1998, Crookston 1997 and Wyckoff and others 1982.]

Silvicultural Intervention Prescriptions

Silvicultural interventions were designed to minimize impact to sites while meeting the key indicators. The desired condition for the sites is a stand structure representative of those created and maintained in a Type 1 fire regime (a forest of many age classes with diverse canopy structure and spatial distribution of trees that is fire resilient).

Cleanings refer to the removal of one species to favor another. Weeding can mean releasing conifer seedlings from competing vegetation, or as it is used in this analysis, it denotes the

removal of vegetation competing with favored trees. Weedings and cleanings mold future stand structure, determining future species composition and individual tree growth (Graham and others 1999).

Free thinning, sometimes called a crop tree thinning, primarily releases specific trees. This method favors specific trees while the remainder of the stand goes untreated. It offers the most flexibility for creating various stand structures and compositions (Graham and others 1999)

An uneven-aged strategy will in general favor shade tolerant tree species and stands with multiple canopy layers. Crown fire potential would be high except in dry ponderosa pine sites where low crown densities can be achieved with the selection system. The uneven-aged management strategy utilized in this analysis is based upon work by Hollenstein and others (In Prep.). It utilizes a hybrid approach where some large trees (greater than the upper DBH limit) are retained and the stand is managed with a relatively flat diameter distribution (q ratio = 1.25) with a crown closure of approximately 40%.

Fiber production and economics were not primary considerations in the prescription development.

Fire Behavior Predictions

CFFBPS, NEXUS and CFAFM were utilized to simulate fire behavior to assess the relative fire potential in the sites as they progressed through time. Canopy fuels (effective CBH and CBD) were estimated in CFAFM using the procedures developed by Reinhardt and others (In Prep.).

Surface fuels were represented by standard fire behavior fuel models (US and Canadian). Surface fuel models were assumed to remain static through the projection period. Any fuels created during implementation of treatment strategies would be treated to return surface loading to pre-treatment levels.

Scorch heights are estimated based upon projected final surface intensity using Van Wagner scorch equation with an ambient air Temperature of 80°F. In NEXUS, this includes any increase in intensity due to crown fuel consumption (CFB). Flame lengths calculated for NEXUS and CFFBPS simulations are projected using final surface intensity. This includes any increased intensity due to crown fuel consumption. Scorch height and flame lengths are displayed in Appendix C.

Canopy Fuel Characteristics

Canopy Fuel Characteristics (CBH, CBD and CFL) for all fire simulations were calculated in CFAFM. CFAFM was originally designed to calculate canopy fuel characteristics utilizing the procedure developed by Reinhardt and others (In Prep.) from simple stand tables. CFAFM was modified to accept FVS tree list records. FVS tree list text files for each simulation cycle to be evaluated were imported into Excel and then into CFAFM after minor editing.

Trees less than 1" diameter are excluded from crown fuel loadings as they are insignificant to canopy fuel loading at the densities they occur in the stands, although they can contribute to crown fire development as ladder fuels and in certain stand structural stages they contribute to critical CBD. The surface fuels were not adjusted to reflect an additional loading from these trees. All tree crown weights were calculated with the same crown status (dominant), regardless of the trees actual status in the stand. This most likely overestimates the crown weights of smaller trees.

Only major conifer species were considered in the calculation of canopy fuel characteristic. As they probably do not support crown fire spread, hardwoods such as aspen (Populus tremuloides Michaux) were excluded (Sando and Wick 1972, Fechner and Barrows 1976).

The running mean for Canopy bulk density was calculated on a 11-foot running mean rather than 15- feet as recommended by Reinhardt and others (In Prep.). This was done to reduce the instances where CBD was not calculated on the 15-foot running mean and it seems that a 11-foot band of crown fuels is still deep enough to be relevant to crown fire behavior. When CBD running mean does not exceed 0.037 kg m^{-3} a CBH of 200-feet is applied to the site. At first observation, this may appear to inflate the values for $I'_{initiation}$, $R'_{initiation}$ and TI excessively. However, the correct interpretation is that the stand conditions are insufficient to allow crown fire to initiate. Where this happens it is possible that the TI will have a much higher value than CI.

FBPS (US)

Although Alexander (Armstrong, 1998) relates that R_{active} as proposed by Rothermel's (1991) crown fire spread rate model should utilize a constant of 2.0 rather than 3.34, as the 3.34 tends to over predict R_{active}. Rothermel's constant is utilized in both NEXUS and CFAFM and that convention is maintained in this analysis.

$R_{crown} = 3.34(R_{10})_{40\%}$ (Rothermel 1991) where $(R_{10})_{40\%}$ is the spread rate predicted with Rothermel's (1972) surface fire model using the fuel characteristics for Fuel Model 10 and midflame windspeed set at 40% of the 20-foot open windspeed.

$R_{active} = 3.34\left(\dfrac{I_R\xi(1+\phi_w+\phi_s)}{\rho_b\varepsilon Q_{ig}}\right)_{FM10}$ where all terms are defined in Table 21 and are evaluated for characteristics of Fuel Model 10.

The surface fuels within the sites were best represented as in Table 11.

Surface fuel models were assumed to remain static through the projection period. Any fuels created during implementation of treatment strategies would be treated to return surface loading to pre-treatment levels.

Wind reduction factors (Andrews 1986) and fuel moisture adjustments (Rothermel 1983) were determined for each site based upon the degree of sheltering and shading at each site. They were established at the start of the simulation and were held constant through all projections and alternatives (Table 11 and Appendix A). As surface fuels moistures vary as a function of canopy cover, keeping the fuel moistures as exposed during the simulation period represents a worse case projection.

Table 11 – FBPS (US) Fuel Model, Wind Reduction Factors and Fuel Moisture Adjustments

Site	Fuel Model	Wind Reduction Factor	Moisture Adjustment
104521.004	2	0.3	Fuels Exposed
104521.016	5	0.3	Fuels Exposed
104521.018	2	0.2	Fuels Exposed

CFAFM

CFAFM does not utilize wind vectoring. All projections are with winds upslope (alignment with aspect).

NEXUS

West winds are used for simulations. The following options settings were utilized: crown fire enabled, straight line CFB form and foliar moisture effect (FME) disabled. FME was not used since it is not an option in CFAFM and usually only applies to Fuel Model C-6 in CFFBPS.

CFFBPS

Calculations were done utilizing FBP Version 97.0 software by REMSOFT (1993, 1997). Fuel model C-7 (ponderosa pine - Douglas-fir) and west winds were used for all simulations.

In the CFFBPS, RSO'_{active} is calculated as a function of the critical surface intensity (CSI) and surface fuel consumption. Since CSI is a function of CBH and FMC, using CBH as calculated by CFAFM (i.e. 200-foot CBH when critical CBD is not exceeded) may yield inappropriate results since the CFFBPS is based upon empirical observations (i.e. default CBH is 10-feet for model C-7) and a 200-foot CBH was most likely not within the original data set.

Results and Evaluation

The following management alternatives were simulated for the representative sites:

Table 12 – Management Alternatives

Site	Alternative Name	FVS Run Name	Description
104521.004	Base NM	521004_bnm_rg3	Base Alternative - No management with minor regeneration at intermediate periods (50tpa / 20 years).
104521.004	Alt2	521004_alt2	Cleaning - remove all Douglas-fir at year 1999 with minor regeneration at intermediate periods (50tpa / 20 years).
104521.016	Base NM	521016_bnm	Base Alternative - No management with minor regeneration at intermediate periods (50tpa / 20 years).
104521.016	Alt2	521016_alt2	Uneven-aged management, Free thin at year 2009 to 500 tpa in 0-3" diameter class, Q=1.25, BA=60, maximum diameter=25, minimum diameter=1, regeneration of ponderosa pine 100 tpa I year after intervention
104521.018	Base NM	521018_bnm	Base Alternative - No management with minor regeneration at intermediate periods (50tpa / 20 years).
104521.018	Alt2	521018_alt2	Cleaning - remove all lodgepole pine at year 1999 with minor regeneration at intermediate periods (50tpa / 20 years).

Site	Alternative Name	FVS Run Name	Description
104521.018	Alt21	521018_alt21	Cleaning - remove all lodgepole pine at year 1999 with planting within 3 years at density of 436 tpa, 80% survival and then minor regeneration at intermediate periods (50tpa / 20 years).

The results of the simulations are summarized in Tables 13 – 19. The summaries are by site, alternative, year and fire behavior tool and document the simulations performance relative to the key indicators established for this analysis. Details of the simulations are contained in Appendix B (FVS) and D (Fire Behavior).

Comparisons of stand structure (SVS) and canopy fuel profile for each site and alternative at the beginning and end of the projections are contained in Appendix E. "Side-by-side" comparisons of stand structure (SVS) and canopy fuel profile could be done at any point during the simulation period to support the analysis and development of alternatives. The comparison in Figure 9 shows the stand structure and canopy fuel profile at the point in the simulation where stand conditions would support active crown fire.

Figure 9 – Example Stand Structure (SVS) – Canopy Fuel Profile Comparison (CFAFM),
Site 104521.016 – Base No Management - 2059
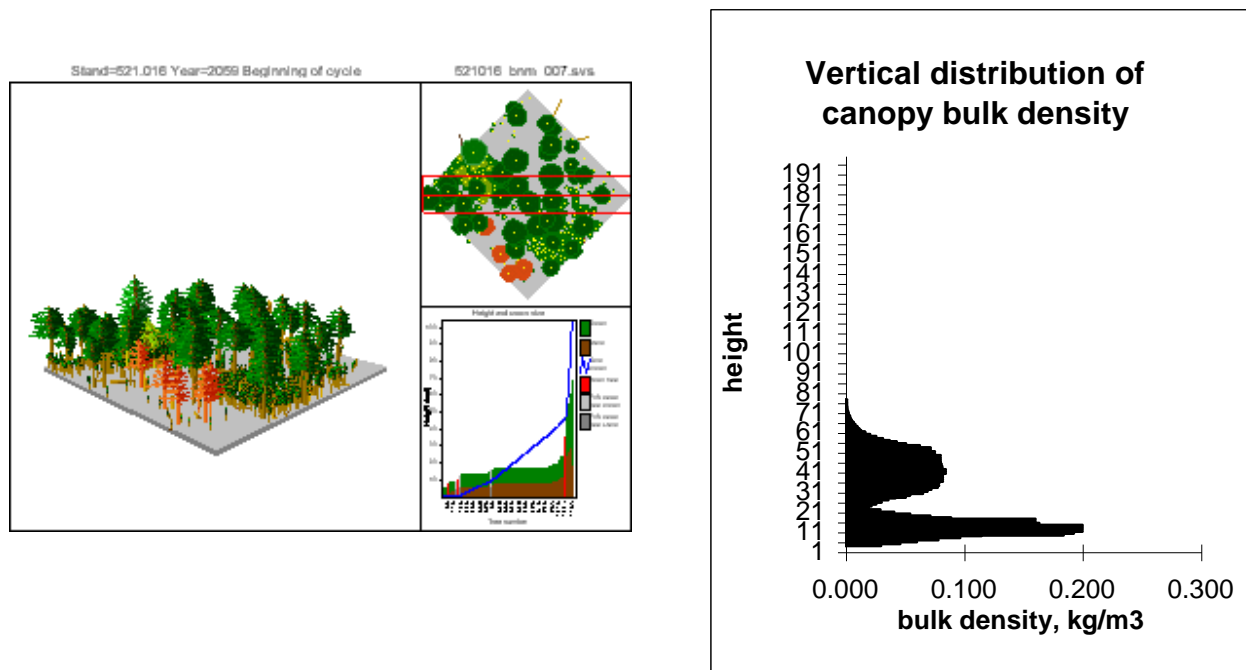
Site 104521.004 - Dry Site Ponderosa Pine

FBPS (US)

On balance, this site not very susceptible to initiation or sustained spread of crown fire. However, without management, CBD will increase to near critical level in approximately 20 years, along with a significant decrease in CBH. The primary cause of this increased susceptibility is in-growth of the existing Douglas-fir component. Implementation of Alternative 2 effectively reduces the site's susceptibility to crown fire for a period of 80 years. After

removal of the Douglas-fir, the site does not exceed 0.037 kg m^{-3} until the end of the projection period. All key indicators are met with Alternative 2.

CFFBPS

Predicted surface intensities are significantly higher than in FBPS (US). $I'_{initiation}$ is similar to FBPS (US) estimates but initiation of crown fire is at much lower windspeeds (e.g. 1999 TI_{wsv} of 1.6 mi hr^{-1}). Type of fire compares favorably with CI_{wsv}, TI_{wsv}, $ISI'_{initiation}$ and ISI'_{active}. A CBH of 200-feet was used for three cycles in Alternative 2 but the treatment does not meet the key indicator for crown fire initiation by the end of the simulation.

Site 104521.016 – Managed Ponderosa Pine

FBPS (US)

Relatively speaking this site is the most susceptible for initiation and spread of crown fire. The hazard is primarily related to in-growth of the ponderosa pine understory that was established after previous treatments. Without management TI decrease from approximately 20 mi hr^{-1} to 0 mi hr^{-1} in 20 years, which reflects a very low CBH. Similarly, CI decreases over the projection period as CBD increases. Implementation of Alternative 2 (uneven-aged management) reduces susceptibility for most of the projection period. Although CFAFM, which utilizes the exponential CFB form, shows a susceptible period when regeneration established following earlier interventions reaches critical CBD. NEXUS shows the fire type as surface with a CFB of 0.04 even though $I'_{initiation} < I$. This strategy does not fully meet the key indicators. It needs further refinement before implementation but reflects the general success of the strategy.

CFFBPS

Predicted surface intensities and rates of spread are significantly higher than in FBPS (US). $I'_{initiation}$ is similar to FBPS (US) estimates but initiation of crown fire is at much lower windspeeds (e.g. 1999 TI_{wsv} of 2.7 mi hr^{-1}). Even with intervention, the site remains susceptible to initiation and spread of crown fire throughout the projection period.

Fire type (Active) based upon CFB is not consistent with CI_{wsv}, and ISI'_{active}. Calculated CBD are not sufficient to support active crown fire (CI_{wsv}, and ISI'_{active} as compared with an open 20-foot windspeed of 11.0 mi hr^{-1}).

Site 104521.018 – Lodgepole Pine Component

FBPS (US)

Counter to impressions this representative site is the least susceptible to initiation and spread of crown fire. Although CBD approaches, 0.010 kg m^{-3} throughout the simulation period CBH remains relatively high. Although the site may not be susceptible to initiation of crown fire, it is susceptible to the spread of crown fire that initiates in adjacent sites (CI is less than TI during portions of the simulation). In addition, without intervention site conversion to lodgepole pine continues. Alternative 2 removes all of the lodgepole pine form the site. Alternative 21 is the same as Alternative 2 except with the planting of ponderosa pine rather than reliance on existing advance regeneration. Implementation of Alternative 2 reduces susceptibility throughout the simulation period. Planting the site following removal of the lodgepole pine increases the susceptibility in the last half of the projection period. Therefore planting is not recommended at the densities used in this analysis.

Table 13 – Simulation Results - Site 104521.004 – Base No Management

	Site	521.004	521.004	521.004	521.004	521.004	521.004
	Year	1999	2019	2039	2059	2079	2099
	O 20 ft windspeed (mi hr^{-1})	14.7	14.7	14.7	14.7	14.7	14.7
	BA (ft^2 ac^{-1})	84	100	117	136	159	184
Stand	TPA (stems ac^{-1})	196	168	196	229	268	308
Characteristics	SDI	161	180	210	245	286	331
	HT (ft)	37	45	52	58	63	66
	QMD (inches)	8.9	10.5	10.5	10.4	10.4	10.5
	Stand Resiliency Index	4.1	3.8	3.9	4.1	4.2	4.4
	CBD (kg m^{-3})	0.0420	0.1166	0.0577	0.0616	0.0670	0.0737
	Max 1 ft CBD (kg m^{-3})	0.0492	0.1232	0.0579	0.0616	0.0670	0.0737
Canopy	Stand Height (ft)	26	55	48	56	62	66
Characteristics	CBH (ft)	17	12	22	24	25	26
	CFL (lbs ft^{-2})	0.0740	0.2180	0.1120	0.1290	0.1490	0.1660
Key Old Growth	Large Live Trees 18"+ and $\geq$15 12"+	Y	Y	Y	Y	Y	Y
Characteristics	>20% Crown Closure (%)	55	61	66	73	79	NC
	I (Btu ft^{-1} sec^{-1})	428.0	428.0	428.0	428.0	428.0	428.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	569.7	337.9	838.7	953.6	1016.0	1077.5
	$R_{surface}$ (ch hr^{-1})	44.8	44.8	44.8	44.8	44.8	44.8
	$R'_{initiation}$ (ch hr^{-1})	59.7	35.4	87.8	100.1	106.4	112.9
CFAFM	R_{active} (ch hr^{-1})	44.8	69.7	44.8	44.8	44.8	44.8
	R'_{active} (ch hr^{-1})	213.3	76.8	155.1	145.2	133.5	127.9
	Fire Type	Surface	Passive	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.89	0.00	0.00	0.00	0.00
	TI (mph)	17.2	12.1	21.8	23.6	24.5	25.3
	CI (mph)	30.5	13.8	24.0	22.8	21.4	19.9
	Total I (Btu ft^{-1} sec^{-1})	399.0	1704.0	399.0	399.0	399.0	399.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	567.0	336.0	835.0	951.0	1011.0	1072.0
NEXUS	$R_{surface}$ (ch hr^{-1})	42.6	60.1	42.6	42.6	42.6	42.6
	$R'_{initiation}$ (ch hr^{-1})	60.5	35.9	89.1	101.6	108.0	114.5
	R_{active} (ch hr^{-1})	71.1	71.1	71.1	71.1	71.1	71.1
	R'_{active} (ch hr^{-1})	213	77	155	145	134	121
	Fire Type	Surface	Passive	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.61	0.00	0.00	0.00	0.00
	TI (mph)	18.3	13.1	23.1	25.0	25.9	26.8
	CI (mph)	33.8	15.6	26.8	25.5	24.9	22.3
	O 20 ft windspeed (mi hr^{-1})	11.0	11.0	11.0	11.0	11.0	11.0
	Final ISI	22.0	22.0	22.0	22.0	22.0	22.0
	Total I (Btu ft^{-1} sec^{-1})	3074.8	3670.8	3208.6	3270.3	3334.2	3395.6
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	566.7	340.3	834.2	950.5	1010.6	1071.8
	$R_{surface}$ (ch hr^{-1})	31.4	31.4	31.4	31.4	31.4	31.4
CFFBPS	$R'_{initiation}$ (ch hr^{-1})	6.3	3.8	9.3	10.6	11.3	12.0
	Fire Type	Passive	Passive	Passive	Passive	Passive	Passive
	CFB (proportion)	0.86	0.88	0.82	0.80	0.79	0.71
	ISI $_{initiation}$ (TI)	8.0	6.1	10.0	10.7	11.3	11.4
	TI_{wsv} (mph) (20-ft)	1.6	0.0	4.0	4.8	5.3	5.5
	ISI $_{active}$ (CI)	----	45.4	----	----	147.3	93.8
	CI_{wsv} (mph) (20 ft)	----	20.2	----	----	32.9	28.0

Table 14 – Simulation Results - Site 104521.004 – Alternative 2

	Site	521.004	521.004	521.004	521.004	521.004	521.004
	Year	1999	2019	2039	2059	2079	2099
	O 20 ft windspeed (mi hr^{-1})	14.7	14.7	14.7	14.7	14.7	14.7
	BA (ft^2 ac^{-1})	84	74	91	105	120	136
Stand	TPA (stems ac^{-1})	196	153	168	202	242	281
Characteristics	SDI	161	138	167	194	223	254
	HT (ft)	37	39	48	53	56	58
	QMD (inches)	8.9	10.2	10.0	9.8	9.5	9.4
	Stand Resiliency Index	4.1	3.7	3.8	4.0	4.2	4.4
	CBD (kg m^{-3})	0.0420	0.0273	0.0316	0.0349	0.0354	0.0378
	Max 1 ft CBD (kg m^{-3})	0.0492	0.0289	0.0316	0.0349	0.0354	0.0378
Canopy	Stand Height (ft)	26	0	0	0	0	52
Characteristics	CBH (ft)	17	200	200	200	200	39
	CFL (lbs ft^{-2})	0.0740	0.0510	0.0580	0.0710	0.0770	0.0820
Key Old Growth	Large Live Trees 18"+ and $\geq$15 12"+	Y	Y	Y	Y	Y	Y
Characteristics	>20% Crown Closure (%)	55	51	55	55	55	55
	I (Btu ft^{-1} sec^{-1})	428.0	428.0	428.0	428.0	428.0	428.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	569.7	22988.1	22988.1	22988.1	22988.1	1979.5
	$R_{surface}$ (ch hr^{-1})	44.8	44.8	44.8	44.8	44.8	44.8
	$R'_{initiation}$ (ch hr^{-1})	59.7	2407.9	2407.9	2407.9	2407.9	207.3
CFAFM	R_{active} (ch hr^{-1})	44.8	44.8	44.8	44.8	44.8	44.8
	R'_{active} (ch hr^{-1})	213.3	328.0	283.2	256.4	252.6	236.5
	Fire Type	Surface	Surface	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.00	0.00	0.00
	TI (mph)	17.2	140.3	140.3	140.3	140.3	36.0
	CI (mph)	30.5	41.8	37.5	34.9	34.5	32.9
	Total I (Btu ft^{-1} sec^{-1})	399.0	399.0	399.0	399.0	399.0	399.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	567.0	22881.0	22881.0	22881.0	22881.0	1970.0
NEXUS	$R_{surface}$ (ch hr^{-1})	42.6	42.6	42.6	42.6	42.6	42.6
	$R'_{initiation}$ (ch hr^{-1})	60.5	2443.1	2443.1	2443.1	2443.1	210.4
	R_{active} (ch hr^{-1})	71.1	71.1	71.1	71.1	71.1	71.1
	R'_{active} (ch hr^{-1})	213	328	256	256	253	237
	Fire Type	Surface	Surface	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.00	0.00	0.00
	TI (mph)	18.3	147.0	147.0	147.0	147.0	37.9
	CI (mph)	33.8	46.2	38.7	38.7	38.3	36.5
	Final ISI	22.0	22.0	22.0	22.0	22.0	22.0
	O 20 ft windspeed (mi hr^{-1})	11.0	11.0	11.0	11.0	11.0	11.0
	Total I (Btu ft^{-1} sec^{-1})	3074.8	2808.4	2801.4	2801.4	2801.4	2987.8
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	566.7	22866.5	22866.5	22866.5	22866.5	1969.0
	$R_{surface}$ (ch hr^{-1})	31.4	31.4	31.3	31.3	31.3	31.3
CFFBPS	$R'_{initiation}$ (ch hr^{-1})	6.3	255.5	255.5	255.5	255.5	22.0
	Fire Type	Passive	Surface	Surface	Surface	Surface	Passive
	CFB (proportion)	0.86	0.00	0.00	0.00	0.00	0.51
	ISI initiation (TI)	8.0	----	----	----	----	17.1
	TI_{wsv} (mph) (20-ft)	1.6	----	----	----	----	9.8
	ISI active (CI)	----	----	----	----	----	----
	CI_{wsv} (mph) (20 ft)	----	----	----	----	----	----

Table 15 – Simulation Results - Site 104521.016 – Base No Management

	Site	521.016	521.016	521.016	521.016	521.016	521.016
	Year	1999	2019	2039	2059	2079	2099
	O 20 ft windspeed (mi hr^{-1})	14.7	14.7	14.7	14.7	14.7	14.7
	BA (ft^2 ac^{-1})	69	88	119	141	154	166
Stand	TPA (stems ac^{-1})	1240	1104	1095	1024	974	938
Characteristics	SDI	182	236	300	338	360	379
	HT (ft)	48	52	55	57	57	58
	QMD (inches)	3.0	3.8	4.5	5.0	5.4	5.7
	Stand Resiliency Index	7.0	6.7	6.5	6.3	6.2	6.1
	CBD (kg m^{-3})	0.0513	0.0648	0.0852	0.1588	0.1417	0.1344
	Max 1 ft CBD (kg m^{-3})	0.0533	0.0669	0.1055	0.2005	0.1778	0.1414
Canopy	Stand Height (ft)	44	51	55	57	58	59
Characteristics	CBH (ft)	19	2	4	4	8	11
	CFL (lbs ft^{-2})	0.1040	0.1390	0.1890	0.2460	0.2410	0.2470
Key Old Growth	Large Live Trees 18"+ and $\geq$15 12"+	Y	Y	Y	Y	Y	Y
Characteristics	>20% Crown Closure (%)	40	52	64	69	73	NC
	I (Btu ft^{-1} sec^{-1})	428.0	428.0	428.0	428.0	428.0	428.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	673.1	23.0	65.0	65.0	183.9	296.5
	$R_{surface}$ (ch hr^{-1})	44.8	44.8	44.8	44.8	44.8	44.8
	$R'_{initiation}$ (ch hr^{-1})	70.5	2.4	6.8	6.8	19.3	31.1
CFAFM	R_{active} (ch hr^{-1})	44.8	72.6	72.6	72.6	72.6	71.6
	R'_{active} (ch hr^{-1})	174.5	138.1	105.1	56.4	63.1	66.6
	Fire Type	Surface	Passive	Passive	Active	Active	Active
	CFB (proportion)	0.00	1.00	1.00	1.00	1.00	1.00
	TI (mph)	19.1	0.0	0.0	0.0	7.3	11.0
	CI (mph)	26.2	22.0	17.8	10.6	11.7	12.2
	Total I (Btu ft^{-1} sec^{-1})	369.0	874.0	1306.0	3043.0	2994.0	3053.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	670.0	23.0	65.0	65.0	183.0	295.0
NEXUS	$R_{surface}$ (ch hr^{-1})	39.4	50.9	55.1	68.7	68.7	68.7
	$R'_{initiation}$ (ch hr^{-1})	71.5	2.4	6.9	6.9	19.5	31.5
	R_{active} (ch hr^{-1})	68.7	68.7	68.7	68.7	68.7	68.7
	R'_{active} (ch hr^{-1})	174	138	105	56	63	67
	Fire Type	Surface	Passive	Passive	Active	Active	Active
	CFB (proportion)	0.00	0.39	0.53	1.00	1.00	1.00
	TI (mph)	20.9	0.0	0.0	0.0	9.4	12.8
	CI (mph)	29.2	24.7	20.2	12.6	13.8	14.9
	Final ISI	30.0	30.0	30.0	30.0	30.0	30.0
	O 20 ft windspeed (mi hr^{-1})	11.0	11.0	11.0	11.0	11.0	11.0
	Total I (Btu ft^{-1} sec^{-1})	4889.2	5121.8	5443.8	5814.0	5776.7	5810.4
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	669.6	22.9	64.7	64.7	182.9	294.9
	$R_{surface}$ (ch hr^{-1})	47.2	47.1	47.1	47.1	47.1	47.1
CFFBPS	$R'_{initiation}$ (ch hr^{-1})	7.5	0.3	0.7	0.7	2.0	3.3
	Fire Type	Active	Active	Active	Active	Active	Active
	CFB (proportion)	0.95	0.97	0.97	0.97	0.97	0.97
	$ISI_{initiation}$ (TI)	8.8	1.6	2.3	2.3	4.4	5.6
	TI_{wsv} (mph) (20-ft)	2.7	0.0	0.0	0.0	0.0	0.0
	ISI_{active} (CI)	---	---	68.7	33.7	37.4	34.6
	CI_{wsv} (mph) (20 ft)	---	---	24.7	17.1	18.2	18.7

Table 16 – Simulation Results - Site 104521.016 – Alternative 2

	Site	521.016	521.016	521.016	521.016	521.016	521.016
	Year	1999	2019	2039	2059	2079	2099
	O 20 ft windspeed (mi hr^{-1})	14.7	14.7	14.7	14.7	14.7	14.7
	BA (ft^2 ac^{-1})	69	85	84	85	88	89
Stand	TPA (stems ac^{-1})	1240	601	433	351	341	372
Characteristics	SDI	182	203	188	183	186	192
	HT (ft)	48	52	52	52	50	49
	QMD (inches)	3.0	5.1	6.4	6.7	6.9	6.6
	Stand Resiliency Index	7.0	5.8	5.2	5.0	4.9	5.0
	CBD (kg m^{-3})	0.0513	0.0659	0.0592	0.0532	0.0497	0.0442
	Max 1 ft CBD (kg m^{-3})	0.0533	0.0687	0.0615	0.0544	0.0498	0.0525
Canopy	Stand Height (ft)	44	51	52	54	54	54
Characteristics	CBH (ft)	19	21	25	12	29	26
	CFL (lbs ft^{-2})	0.1040	0.1340	0.1250	0.1270	0.1190	0.1150
Key Old Growth	Large Live Trees 18"+ and $\geq$15 12"+	Y	Y	Y	Y	Y	Y
Characteristics	>20% Crown Closure (%)	40	50	48	48	48	46
	I (Btu ft^{-1} sec^{-1})	428.0	428.0	428.0	428.0	428.0	428.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	673.1	782.2	1016.0	337.9	1269.3	1077.5
	$R_{surface}$ (ch hr^{-1})	44.8	44.8	44.8	44.8	44.8	44.8
	$R'_{initiation}$ (ch hr^{-1})	70.5	81.9	106.4	35.4	132.9	112.9
CFAFM	R_{active} (ch hr^{-1})	44.8	44.8	44.8	69.7	44.8	44.8
	R'_{active} (ch hr^{-1})	174.5	135.8	151.1	168.2	180.2	202.4
	Fire Type	Surface	Surface	Surface	Passive	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.89	0.00	0.00
	TI (mph)	19.1	20.9	24.5	12.1	27.9	25.3
	CI (mph)	26.2	21.7	23.5	25.5	26.9	29.3
	Total I (Btu ft^{-1} sec^{-1})	369.0	369.0	369.0	409.0	369.0	369.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	670.0	779.0	1011.0	336.0	1263.0	1072.0
NEXUS	$R_{surface}$ (ch hr^{-1})	39.4	39.4	39.4	40.5	39.4	39.4
	$R'_{initiation}$ (ch hr^{-1})	71.5	83.1	108.0	35.9	134.9	114.5
	R_{active} (ch hr^{-1})	68.7	68.7	68.7	68.7	68.7	68.7
	R'_{active} (ch hr^{-1})	174	136	151	168	180	202
	Fire Type	Surface	Surface	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.04	0.00	0.00
	TI (mph)	20.9	22.7	26.4	13.9	29.9	27.2
	CI (mph)	29.2	24.4	26.4	28.5	29.9	32.5
	Final ISI	30.0	30.0	30.0	30.0	30.0	30.0
	O 20 ft windspeed (mi hr^{-1})	11.0	11.0	11.0	11.0	11.0	11.0
	Total I (Btu ft^{-1} sec^{-1})	4889.2	5076.6	4998.7	5034.8	4948.9	4933.5
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	669.6	778.0	1010.6	336.1	1262.6	1071.8
	$R_{surface}$ (ch hr^{-1})	47.2	47.2	47.1	47.1	47.1	47.1
CFBPS	$R'_{initiation}$ (ch hr^{-1})	7.5	8.7	11.3	3.8	14.1	12.0
	Fire Type	Active	Active	Active	Active	Active	Active
	CFB (proportion)	0.95	0.95	0.94	0.96	0.92	0.93
	ISI $_{initiation}$ (TI)	8.8	9.6	11.3	6.1	12.8	11.6
	TI_{wsv} (mph) (20-ft)	2.7	3.6	5.3	0.0	6.7	5.6
	ISI $_{active}$ (CI)	---	190.7	---	---	---	---
	CI_{wsv} (mph) (20 ft)	---	35.6	---	---	---	---

Table 17 – Simulation Results - Site 104521.018 – Base No Management

	Site	521.018	521.018	521.018	521.018	521.018	521.018
	Year	1999	2019	2039	2059	2079	2099
	O 20 ft windspeed (mi hr^{-1})	13.2	13.2	13.2	13.2	13.2	13.2
	BA (ft^2 ac^{-1})	75	94	109	119	121	110
Stand	TPA (stems ac^{-1})	162	152	192	230	259	284
Characteristics	SDI	142	168	198	220	228	228
	HT (ft)	47	52	52	57	59	59
	QMD (inches)	9.3	10.7	10.2	10.2	9.3	8.6
	Stand Resiliency Index	3.9	3.7	3.9	4.1	4.3	4.5
	CBD (kg m^{-3})	0.0729	0.0908	0.0995	0.1019	0.0986	0.0884
	Max 1 ft CBD (kg m^{-3})	0.0814	0.0976	0.1021	0.1041	0.1097	0.0960
Canopy	Stand Height (ft)	46	52	55	58	59	59
Characteristics	CBH (ft)	18	20	22	24	25	27
	CFL (lbs ft^{-2})	0.1320	0.1570	0.1730	0.1790	0.1750	0.1630
Key Old Growth	Large Live Trees 18"+ and $\geq$15 12"+	Y	Y	Y	Y	Y	Y
Characteristics	>20% Crown Closure (%)	47	53	58	61	62	---
	I (Btu ft^{-1} sec^{-1})	386.0	386.0	386.0	386.0	386.0	386.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	620.7	727.0	838.7	955.6	1016.0	1140.3
	$R_{surface}$ (ch hr^{-1})	18.8	18.8	18.8	18.8	18.8	18.8
	$R'_{initiation}$ (ch hr^{-1})	30.2	35.4	40.8	46.5	49.5	55.5
CFAFM	R_{active} (ch hr^{-1})	18.8	18.8	18.8	18.8	18.8	18.8
	R'_{active} (ch hr^{-1})	122.8	98.6	90.0	87.8	90.8	101.2
	Fire Type	Surface	Surface	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.00	0.00	0.00
	TI (mph)	18.0	20.4	22.7	25.1	26.3	28.6
	CI (mph)	30.8	26.3	24.6	24.2	24.8	26.8
	Total I (Btu ft^{-1} sec^{-1})	151.0	151.0	151.0	151.0	151.0	151.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	618.0	724.0	835.0	951.0	1011.0	1135.0
NEXUS	$R_{surface}$ (ch hr^{-1})	11.7	11.7	11.7	11.7	11.7	11.7
	$R'_{initiation}$ (ch hr^{-1})	48.0	56.2	64.8	73.9	78.5	88.1
	R_{active} (ch hr^{-1})	34.7	34.7	34.7	34.7	34.7	34.7
	R'_{active} (ch hr^{-1})	123	99	90	88	91	101
	Fire Type	Surface	Surface	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.00	0.00	0.00
	TI (mph)	38.7	43.4	48.2	53.1	55.5	60.3
	CI (mph)	33.4	29.0	27.1	26.7	27.3	29.6
	Final ISI	26.7	26.7	26.7	26.7	26.7	26.7
	O 20 ft windspeed (mi hr^{-1})	11.0	11.0	11.0	11.0	11.0	11.0
	Total I (Btu ft^{-1} sec^{-1})	4345.9	4500.2	4545.4	4588.4	4583.0	4468.6
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	617.4	723.1	834.2	950.5	1010.6	1134.2
	$R_{surface}$ (ch hr^{-1})	40.8	40.8	40.8	40.8	40.8	40.8
CFFBPS	$R'_{initiation}$ (ch hr^{-1})	6.9	8.1	9.3	10.6	11.3	12.7
	Fire Type	Active	Active	Active	Active	Passive	Passive
	CFB (proportion)	0.93	0.92	0.91	0.90	0.90	0.88
	$ISI_{initiation}$ (TI)	8.4	9.2	10.0	10.7	11.3	12.0
	TI_{wsv} (mph) (20-ft)	2.2	3.2	4.0	4.8	5.3	5.9
	ISI_{active} (CI)	96.9	62.1	54.7	53.1	55.3	64.7
	CI_{wsv} (mph) (20 ft)	28.4	23.6	22.2	21.9	22.4	24.0

Table 18 – Simulation Results - Site 104521.018 – Alternative 2

	Site	521.018	521.018	521.018	521.018	521.018	521.018
	Year	1999	2019	2039	2059	2079	2099
	O 20 ft windspeed (mi hr^{-1})	13.2	13.2	13.2	13.2	13.2	13.2
	BA (ft^2 ac^{-1})	75	74	90	101	108	111
Stand	TPA (stems ac^{-1})	162	115	157	196	228	256
Characteristics	SDI	142	131	162	187	203	212
	HT (ft)	47	49	53	56	58	57
	QMD (inches)	9.3	10.9	10.2	9.7	9.3	8.9
	Stand Resiliency Index	3.9	3.4	3.7	4.0	4.2	4.4
	CBD (kg m^{-3})	0.0729	0.0683	0.0743	0.0775	0.0755	0.0717
	Max 1 ft CBD (kg m^{-3})	0.0814	0.0716	0.0818	0.0837	0.0798	0.0735
Canopy	Stand Height (ft)	46	48	53	55	57	58
Characteristics	CBH (ft)	18	21	23	24	26	27
	CFL (lbs ft^{-2})	0.1320	0.1230	0.1390	0.1490	0.1500	0.1490
Key Old Growth	Large Live Trees 18"+ and $\geq$15 12"+	Y	Y	Y	Y	Y	Y
Characteristics	>20% Crown Closure (%)	47	39	49	53	55	---
	I (Btu ft^{-1} sec^{-1})	386.0	386.0	386.0	386.0	386.0	386.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	620.7	782.2	896.5	955.6	1077.5	1140.3
	$R_{surface}$ (ch hr^{-1})	18.8	18.8	18.8	18.8	18.8	18.8
	$R'_{initiation}$ (ch hr^{-1})	30.2	38.1	43.6	46.5	52.5	55.5
CFAFM	R_{active} (ch hr^{-1})	18.8	18.8	18.8	18.8	18.8	18.8
	R'_{active} (ch hr^{-1})	122.8	131.0	120.5	115.5	118.6	124.7
	Fire Type	Surface	Surface	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.00	0.00	0.00
	TI (mph)	18.8	21.5	23.9	25.1	27.4	28.6
	CI (mph)	30.2	32.3	30.4	29.5	30.1	31.2
	Total I (Btu ft^{-1} sec^{-1})	151.0	151.0	151.0	151.0	151.0	151.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	618.0	779.0	892.0	951.0	1072.0	1136.0
NEXUS	$R_{surface}$ (ch hr^{-1})	11.7	11.7	11.7	11.7	11.7	11.7
	$R'_{initiation}$ (ch hr^{-1})	48.0	60.4	69.3	73.9	83.3	88.1
	R_{active} (ch hr^{-1})	34.7	34.7	34.7	34.7	34.7	34.7
	R'_{active} (ch hr^{-1})	123	131	120	115	119	125
	Fire Type	Surface	Surface	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.00	0.00	0.00
	TI (mph)	38.7	45.8	50.6	53.1	57.9	60.3
	CI (mph)	33.4	35.0	33.0	32.0	32.6	33.8
	Final ISI	26.7	26.7	26.7	26.7	26.7	26.7
	O 20 ft windspeed (mi hr^{-1})	11.0	11.0	11.0	11.0	11.0	11.0
	Total I (Btu ft^{-1} sec^{-1})	4345.9	4300.6	4378.4	4364.6	4411.0	4400.6
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	617.4	778.0	891.8	950.5	1071.8	1134.2
	$R_{surface}$ (ch hr^{-1})	40.8	31.4	31.3	31.3	31.3	31.3
CFBPS	$R'_{initiation}$ (ch hr^{-1})	6.9	8.7	10.0	10.6	12.2	12.7
	Fire Type	Active	Active	Active	Active	Passive	Passive
	CFB (proportion)	0.93	0.92	0.90	0.90	0.90	0.88
	$ISI_{initiation}$ (TI)	8.4	9.6	10.4	10.7	11.6	12.0
	TI_{wsv} (mph) (20-ft)	2.2	3.6	4.4	4.8	5.6	5.9
	ISI_{active} (CI)	96.9	127.2	91.7	82.6	87.9	102.3
	CI_{wsv} (mph) (20 ft)	28.4	31.3	27.8	26.7	27.3	29.0

Table 19 – Simulation Results - Site 104521.018 – Alternative 21

	Site	521.018	521.018	521.018	521.018	521.018	521.018
	Year	1999	2019	2039	2059	2079	2099
	O 20 ft windspeed (mi hr^{-1})	13.2	13.2	13.2	13.2	13.2	13.2
	BA (ft^2 ac^{-1})	75	73	97	116	130	136
Stand	TPA (stems ac^{-1})	162	458	487	508	517	511
Characteristics	SDI	142	170	216	252	277	287
	HT (ft)	47	51	53	56	58	58
	QMD (inches)	9.3	5.4	6.0	6.5	6.8	7.0
	Stand Resiliency Index	3.9	5.4	5.4	5.4	5.3	5.3
	CBD (kg m^{-3})	0.0729	0.0668	0.0745	0.0770	0.0917	0.1107
	Max 1 ft CBD (kg m^{-3})	0.0814	0.0697	0.0813	0.0831	0.1147	0.1303
Canopy	Stand Height (ft)	46	48	52	55	57	58
Characteristics	CBH (ft)	18	21	8	6	7	9
	CFL (lbs ft^{-2})	0.1320	0.1200	0.1570	0.1820	0.2030	0.2130
Key Old Growth	Large Live Trees 18"+ and $\geq$15 12"+	Y	Y	Y	Y	Y	Y
Characteristics	>20% Crown Closure (%)	47	43	53	60	64	---
	I (Btu ft^{-1} sec^{-1})	386.0	386.0	386.0	386.0	386.0	386.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	620.7	782.2	183.9	119.5	150.5	219.4
	$R_{surface}$ (ch hr^{-1})	18.8	18.8	18.8	18.8	18.8	18.8
	$R'_{initiation}$ (ch hr^{-1})	30.2	38.1	9.0	5.8	7.3	10.7
CFAFM	R_{active} (ch hr^{-1})	18.8	18.8	18.8	18.8	18.8	18.8
	R'_{active} (ch hr^{-1})	122.8	133.9	120.2	116.2	97.6	80.8
	Fire Type	Surface	Surface	Passive	Passive	Passive	Passive
	CFB (proportion)	0.00	0.00	0.90	0.95	0.94	0.86
	TI (mph)	18.8	21.5	6.4	4.1	5.3	7.6
	CI (mph)	30.2	32.8	30.4	29.6	26.1	22.8
	Total I (Btu ft^{-1} sec^{-1})	151.0	151.0	151.0	209.0	154.0	151.0
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	618.0	779.0	183.0	119.0	150.0	218.0
NEXUS	$R_{surface}$ (ch hr^{-1})	11.7	11.7	11.7	13.8	11.8	11.7
	$R'_{initiation}$ (ch hr^{-1})	48.0	60.4	14.2	9.2	11.6	17.0
	R_{active} (ch hr^{-1})	34.7	34.7	34.7	34.7	34.7	34.7
	R'_{active} (ch hr^{-1})	123	134	120	116	98	81
	Fire Type	Surface	Surface	Surface	Surface	Surface	Surface
	CFB (proportion)	0.00	0.00	0.00	0.09	0.01	0.00
	TI (mph)	38.7	45.8	15.4	10.8	13.1	17.7
	CI (mph)	33.4	35.6	32.9	32.2	28.4	24.7
	Final ISI	26.7	26.7	26.7	26.7	26.7	26.7
	O 20 ft windspeed (mi hr^{-1})	11.0	11.0	11.0	11.0	11.0	11.0
	Total I (Btu ft^{-1} sec^{-1})	4345.9	4278.3	4500.0	4639.7	4753.5	4804.7
	$I'_{initiation}$ (Btu ft^{-1} sec^{-1})	617.4	777.9	182.9	118.8	149.7	218.3
	$R_{surface}$ (ch hr^{-1})	40.8	40.7	40.7	40.7	40.7	40.7
CFFBPS	$R'_{initiation}$ (ch hr^{-1})	6.9	8.7	2.0	1.3	1.7	2.4
	Fire Type	Active	Active	Active	Active	Active	Active
	CFB (proportion)	0.93	0.92	0.95	0.95	0.95	0.95
	ISI $_{initiation}$ (TI)	8.4	9.6	4.4	3.2	3.7	4.7
	TI_{wsv} (mph) (20-ft)	2.2	3.6	0.0	0.0	0.0	0.0
	ISI $_{active}$ (CI)	96.9	151.9	91.0	83.8	61.2	48.1
	CI_{wsv} (mph) (20 ft)	28.4	33.2	27.7	26.8	23.4	20.9

Although fuel model 5 was selected in CFAFM, the fire behavior calculated is more representative of fuel model 2 fire behavior. The developers are looking into this problem. Nevertheless, the findings for this representative condition are still valid since at the higher intensities calculated by CFAFM the site not very susceptible to crown fire initiation and spread.

CFFBPS

Predicted surface intensities and rates of spread are significantly higher than in FBPS (US). $I'_{initiation}$ is similar to FBPS (US) estimates but initiation of crown fire is at much lower windspeeds (e.g. 1999 TI_{wsv} of 2.2 mi hr^{-1}). With or without intervention, the site remains susceptible to initiation and spread of crown fire throughout the projection period.

Fire type (Active) based upon CFB is not consistent with CI_{wsv}, and ISI'_{active}.   When the calculated CI_{wsv}, and ISI'_{active} are compared with the open 20-foot windspeed of 11.0 mi hr-1 and the final ISI of 26.7 fire type would be classed as passive using the FFE-FVS fire type classifications.

Stand Resiliency Index (SRI)

The Stand Resiliency Index[18] was proposed as a proxy for CBD. The simulation results for CBD along with CBH, CFL, critical flame length, $I'_{initiation}$, $R'_{initiation}$, Torching Index and Crowning Index were analyzed for a correlation with SRI[19]. The results are summarized in Table 20.

There is no correlation between the SRI and any of the conditions for the initiation and spread of crown fires or with the crown fire indices as calculated in this analysis. The best fits are for Crown Base Height, Critical Flame Length, and the Torching Index, but all have an $R^2 < 0.35$. This is a very weak correlation a best.   The best inference that can be made for SRI is that with a higher SRI there is a greater likelihood of having significant stocking in the smaller diameter classes.

Table 20 – Regression Analysis Results - Stand Resiliency Index – Canopy Fuel Characteristics and Fire Behavior

Dependent Variable	R^2	SE
Canopy Bulk Density	0.05971	0.02790
Crown Base Height	0.24044	7.09406
Canopy Fuel Load	0.05292	0.04198
Critical Flame Length	0.26679	2.42880
$R'_{initiation}$	0.11226	38.96720
$I'_{initiation}$	0.19224	364.45872
Torching Index	0.31773	14.15231
Crowning Index	0.10721	5.88557

Fire Behavior Tools

Until FFE-FVS is calibrated for the Central Rockies variant, CFAFM appears to be best suited for this type of analysis. CFAFM utilizes a standardized method for calculating CBH and CBD that can be utilized with either simple stand tables or FVS tree lists. The addition of the Torching and Crowning Index calculations allows for the ordinal ranking of sites for crown fire

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[18] Includes all species and size classes including Aspen
[19] Analysis performed in EXCEL using the regression data analysis option.

hazard. Additionally treatment scenarios can be gamed though use of the fuel deposition feature. It is recommended that the errors associated with fuel model 5 predictions must be accounted for before general use and that the optional CFB forms available in NEXUS be incorporated into CFAFM.

NEXUS and CFFBPS both require CBH and CBD inputs that are calculated in CFAFM.

NEXUS has the ability to conduct multiple simulations and graphically compare the results. This allows for "gaming" different fuel model scenarios more efficiently

CFFBPS consistently simulated fire intensities at much higher levels than NEXUS and CFAFM. This may be the result of an "apples and oranges" comparison due to differences in the fire weather inputs, the inexperience of the user with the system or a drawback to an analysis based upon percentile weather. The CFFDRS indices need to be initialized in the spring. In areas normally covered by snow, the calculations should begin on the 3rd day after snow has essentially left the area to which the danger rating applies with specific starting values for FFMC, DMC and DC (Turner and Lawson 1978). Fire Family Plus calculates the CFFDRS indices based upon the available weather records. This procedure does not allow for needed corrections to the starting values if the weather observations start late or reflect winter precipitation deficiencies. This could introduce bias in the indices calculation.

However, inconsistencies of fire type classification based upon CFB and those using CI_{wsv}, TI_{wsv}, $ISI'_{initiation}$ and ISI'_{active} were noted. The predictions did not seem to be sensitive to changes in CBH as NEXUS and CFAFM.

CFBPS is an empirical model based upon observations of actual fire behavior as contrasted with FBPS (US), which is based upon laboratory experiments. Therefore, it appears that one of the drawbacks of CFFBPS is its inability to adjust to different conditions within a fuel type (i.e. scaling fuel models based upon loading or the ability to create new models). (Reinhardt 2000).

For the above reasons CFFBPS is not the recommended tool for use in this type of analysis in our area.

Conclusions

A process for evaluating crown fire susceptibility was developed that can be used to project crown fire hazard through time The process consists of the following steps:

1. Prepare representative 90th percentile fire weather utilizing Fire Family Plus

2. Inventory sites using standard stand examination procedures.

3. Simulate site structural development for a period of 100 years with no management interventions

4. Calculate canopy fuel profile characteristics using CFAFM

5. Complete fire behavior simulation using 90th percentile fire weather for all cycles.

6. Compare results with key indicators (old growth and "fire safe" characteristics) and prepare alternative treatment strategies.

7. Simulate treatment strategies.

8. Repeat steps 4-6 until desired results achieved.

These same basic steps can be utilized when FFE-FVS is calibrated for the Central Rockies variant.

There is enough variation in stand conditions associated with developing ponderosa pine old growth that it would be ill advised to prepare a "cookbook" of treatment strategies that would be applied without further site-specific analysis. However, the analysis did provide insight into the relative ranking of crown fire hazard in these sites. The analysis indicates a relative ranking of crown fire hazard of the representative stands as follows (highest to lowest):

1. Previously managed ponderosa pine

2. Dry site ponderosa pine

3. Lodgepole component with ponderosa pine

This ranking must be tempered with the knowledge that the driving force of the ranking is the relative abundance of understory trees and the calculated Crown Base Height and the ranking will change depending on these attributes. These stand attributes can be effectively altered with intermediate silvicultural treatments (thinnings, cleaning and weeding) in most instances. Although not simulated, it is recommended that low intensity prescribed fire be applied in these areas on 20-30 year cycle to maintain the stands at low susceptibility.

Additionally, under-planting is not recommended at the densities used in this analysis. It appears that a critical level of understory exists that can be maintained/established without an increase in crown fire hazard. This level is associated with the understory contribution to CBH and CBD. The approximate level should be projected to provide additional management guidance.

Economics was not considered a key indicator for success. Some willingness to pay (WTP) studies indicate that old growth (non market value) is valued at $400-500 per acre in Arizona and New Mexico (Forest Guardians 2000) which would offset most direct treatment costs. Regardless, the economic efficiency of the uneven-aged management treatment could be improved by reducing the level of large tree retention. The revenue associated with these trees would further offset treatment costs.

Observations

The results of this analysis must consider the following limitations:

- Other disturbances (fire, insect and disease, wind etc) were not simulated during the projection period. Their interaction would most likely alter the stand development trajectory.

- The linked models used in CFAFM and NEXUS may not predict actual fire behavior with a great deal of accuracy. The coupled model components have individually been validated or verified to some degree, but the coupled model itself has not (Reinhardt and Scott In Prep.).

- Surface and canopy fuels are not uniform within a stand and windspeeds vary temporally. Crown fire initiation and spread may be highly dependent on small-scale variability (Reinhardt and Scott In Prep.).

- The analysis does not reflect the spread of crown fire between stands.

Although the analysis demonstrates that it is possible to reduce crown fire hazard in ponderosa pine, utilizing intermediate silvicultural treatments (thinnings, cleaning and weeding) and an uneven-aged prescription, it does not mean the sites will not be affected by surface fire. In fact, depending on the surface intensity and scorch height, mortality may be significant enough to jeopardize the continued existence of all but the largest trees. FOFEM[20] (First Order Fire Effects Model) (Reinhardt and Others 1997) predicts that the average probability of mortality (all trees) ranges from 0.67 to 1.00 during all simulations (Appendix C)

In some simulations, the Crowning Index was lower than the Torching Index. Although at first glance it would seem that TI should always be lower than CI that is not always the case. In these instances (TI > CI), the correct interpretation is that the CBH is such that crown fire initiation is difficult if not impossible (i.e. 200ft CBH, TI of 140 mph) but the CBD is high enough that if a crown fire initiated outside the stand the CBD is high enough to sustain the crown fire within the stand.

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[20] Full outputs on file at the Canyon Lakes RD office in Fort Collins, CO. Estimates of mortality were projected using the scorch heights form NEXUS (based upon total intensity) at 80° F. on a stand basis.

Table 21 - Symbols used in the text.

Symbol Definition	
a, b, c	Terms in CFFBPS spread equations specific to a fuel model
B,C,E	Terms in Rothermel's (1972) model, all functions of σ
BUI	Build Up Index
CBD	Crown bulk density, kg m^{-3} lbs ft^{-3}
CBH	Crown base height, m, ft
CI	Crowning Index, km hr^{-1} mi hr^{-1}
CI_{wsv}	Crowning Index – net-vectored wind speed , km hr^{-1} mi hr^{-1}
CFB	Crown fraction burned
CFL	Crown Fuel Load kg m^{-2} lbs ft^{-2}
DC	Drought Code
DMC	Duff Moisture Code
$FFMC$	Fine Fuel Moisture Code
FMC	Crown foliar moisture content, percent
$f(F)$	Fine fuel moisture function in the ISI
$f(W)$	Wind function in the ISI
FME	Foliar moisture effect a crown fire parameter
HPA	Heat (release) per unit area, kJ m^{-2} Btu ft^{-2}
H	Heat yield of fuel, kJ kg^{-1}
I	Byram's fireline intensity, kW m^{-1} Btu ft^{-1} sec^{-1}
$I'_{initiation}$	Critical I for initiating a crown fire, kW m^{-1} Btu ft^{-1} sec^{-1}
I_R	Reaction intensity, kW m^{-2} Btu min^{-1} ft^{-2}
ISI	Initial Spread Index
ISI'_{active}	Critical Initial Spread Index for sustaining a fully-active crown fire
$ISI'_{initiation}$	Critical Initial Spread Index for initiating a crown fire
O	Open (6.1-m) windspeed, km hr^{-1} mi hr^{-1}
Q_{ig}	Heat of preignition, kJ kg^{-1}
R	Forward rate of spread, m min^{-1} ft min^{-1}
R_{final}	R for any type of fire: surface, passive crown, or active crown, m min^{-1} ft min^{-1}
R_{active}	R for a fully-active crown fire, m min^{-1} ft min^{-1}
$R_{surface}$	R for a surface fire, m min^{-1} ft min^{-1}
$R'_{initiation}$	Critical R for initiating a crown fire, m min^{-1} ft min^{-1}
R'_{active}	Critical R for sustaining an active crown fire, m min^{-1} ft min^{-1}
RSI	Initial Forward rate of spread, m min^{-1} ft min^{-1}
RSO'_{active}	Critical R for sustaining an active crown fire, m min^{-1} ft min^{-1}
$RSO'_{initiation}$	Critical R for initiating a crown fire, m min^{-1} ft min^{-1}
S	Mass-flow rate of crown fuel, kg m^{-2} s^{-1}
SDI	Reineke's Stand Density Index
TI	Torching Index, km hr^{-1} mi hr^{-1}
TI_{wsv}	Torching Index – net-vectored wind speed , km hr^{-1} mi hr^{-1}
t_R	Flame residence time, min
U	Mid-flame windspeed, km hr^{-1} mi hr^{-1}
W_f	Weight of fuel consumed in the flaming front, kg m^{-2} lbs ft^{-2}
W_t	Total fuel load, kg m^{-2} lbs ft^{-2}
W_a	Available fuel, or total fuel consumption, kg m^{-2} lbs ft^{-2}
W_o	Fine fuel that can potentially contribute to flaming front, kg m^{-2} lbs ft^{-2}
W_n	W_o with the mineral content removed, kg m^{-2} lbs ft^{-2}
W_{crown}	Weight of available canopy fuel, kg m^{-2} lbs ft^{-2}
WRF	Wind reduction factor
β/β_{op}	Packing ratio/optimum packing ratio
ε	Effective heating number
ξ	Propagating flux ratio
ρ_b	Oven-dry fuelbed bulk density, kg m^{-3}
σ	Surface-area-to-volume ratio of fuel particles, cm^{-1}
ϕ_s	Slope factor
ϕ_w	Wind coefficient
$\phi'_{w (initiation)}$	Critical wind coefficient for crown fire initiation

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